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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD REPORT No.762

Castings Airworthiness

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No. 762

CASTINGS AIRWORTHINESS

Papers presented at the 67th Meeting of the Structures and Materials Panel in
Mierlo, Netherlands, 3-7 October 1988

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PREFACE

There is a strong desire and urgent need among NATO nations to cut cost in military aircraft construction. One way is to exploit the advantages offered by advanced casting technology. Near net shape premium castings show great promise with respect to reducing weight and fabrication cost, in comparison to die forgings, parts sculptured from thick plate and components assembled by riveting, adhesive bonding, welding, brazing or otherwise.

Yet for many years castings have not been regarded as competitive compared to wrought products with a view to meeting the requirements set for critical aircraft components. They were judged to be lacking with respect to quality level and consistency of properties. This has led airworthiness authorities, both military and civil, to impose an additional safety factor, the casting factor, on static strength of cast components.

Fortunately, recent years have shown great improvements in casting technology, with respect to control of mould filling, solidification, porosity, inclusion size and content, microstructure and variability of properties. With these developments in mind the Structures and Materials Panel has undertaken a number of actions.

A Specialists' Meeting on Advanced Casting Technology was held in Brussels, Belgium in April 1982. The proceedings were published as AGARD CP-325. The compilation of a Handbook on Advance Castings, AGARD AG-299, was sponsored.

More was needed, however, to achieve a widespread, economically advantageous, and confident application of castings in primary aircraft structure. Therefore a Workshop Conference on Castings Airworthiness was held in Mierlo, Netherlands in October 1988. The main theme was whether or not a casting factor as mentioned above should be maintained.

A first series of papers addressing this question was presented by airworthiness officials, both military and civil, of the NATO nations. In a second series, aircraft designers reported on their experience with the introduction of premium castings in aircraft construction. A third series of papers provided a forum for casting technologies to present the current state of the art with respect to casting technology and to challenge the continued application of a casting factor. In a final session representatives from the different parties involved tried to assess the situation as it was presented by the previous speakers.

It would have been too much to expect that the Workshop held would invoke a drastic change in current thinking on airworthiness of castings for primary aircraft structure. Those who have to deal with this problem, however, will find that the fine papers presented and the discussion that evolved give them ample support for a wise and balanced decision on the introduction of cast products in aircraft construction.

Finally I would like to express my gratitude to the authors, attendees, interpreters and officials, who have contributed to the success of this Workshop.

H.P.van Leeuwen
Chairman, Subcommittee on
Castings Airworthiness.
December 1988.

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ABSTRACT

The AGARD Structures and Materials Panel held a Workshop on Castings Airworthiness in Mierlo, Netherlands in the Fall of 1988 to consider whether a casting factor, as such, need still be applied to premium quality castings given the improvements in casting technology obtained in recent years.

A first series of papers addressing this question was presented by airworthiness officials, both military and civil, of the NATO nations. In a second series, aircraft designers reported on their experience with the introduction of premium castings in aircraft construction. A third series of papers allowed casting technologists to present the current state of the art with respect to casting technology and to challenge the continued application of a casting factor. A final session provided a forum for representatives from the different parties involved to assess the situation as presented by the previous speakers.

* * *

La Commission des Structures et Matériaux de l'AGARD a organisé une Réunion de Travail sur l'homologation des pièces coulées à Mierlo aux Pays-Bas, en Automne 1988 en vue de déterminer si l'application d'un facteur de fonderie (Casting Factor) aux pièces coulées de première qualité s'avère toujours nécessaire, à la lumière des perfectionnements apportés aux techniques de coulée au cours des dernières années.

Une première série de communications sur ce sujet a été présentée par les services officiels, civils et militaires, des pays membres de l'OTAN. Dans un deuxième temps, des concepteurs d'aéronefs ont rendu compte de leurs connaissances en ce qui concerne l'introduction de pièces de haute qualité dans la fabrication des aéronefs. Une troisième série de communications a permis aux spécialistes en fonderie de présenter l'état de l'art dans le domaine des techniques de coulée et de mettre en cause la continuation de l'utilisation d'un facteur de fonderie.

La session finale a servi de forum pour les tenants des différentes parties qui ont essayé d'evaluer la situation, telle que présentée par les conférenciers précédents.

CONTENTS

U.S. AIR FORCE CERTIFICATION OF CASTINGS

BY

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ABSTRACT

The US Air Force structural certification procedure is described. Static strength and durability and damage tolerance certification requirements are presented. Application to castings is explained, including supporting rationale. Elimination of the casting minimum margin of safety (i.e., factor of safety) can be allowed if a defined procedure is followed. Verification tests and quality assurance requirements are also addressed. Distinction between safety of flight versus non-safety of flight structure and manned versus unmanned applications is made.

INTRODUCTION

Castings are required to meet the same strength, durability and damage tolerance criteria as other metallic structures. The specifics of the analytical procedures, material property data development, and design factors applied to castings may vary from those of wrought structure. Any deviations made are to accommodate the behavior typical of castings.

Until recently, the variability of material properties both within each casting and from casting to casting of the same configuration has frustrated attempts to calculate statistically valid allowables. Recent improvements in casting technology are providing an adequately stable data base to attempt the treatment of cast material properties on the same basis as wrought product properties. This attempt has so far succeeded with one specific aluminum casting application and is being considered for other applications (Reference 1).

We will first review the overall qualification procedure, as it is relevant to cast structure, and then proceed to the specific approaches taken for castings. As distinctions can be made for castings with respect to the topics of materials characterization, static strength, durability, and damage tolerance, they will be expanded upon here.

QUALIFICATION PROCESS

The Aircraft Structural Integrity Program (ASIP) described by MIL-STD-1530 (Reference 2) guides the progression of design activities during Full Scale Development (FSD). These activities proceed from the material screening stage through preliminary design, design data development, development (subcomponent) tests, and culminate in full scale tests. The pre-FSD structural technology transition criteria of Reference 3 gives further guidance for the assessment of material properties from laboratory development to design and test. Specific structural design qualification guidelines are provided to the contractor by MIL-A-87221 (Reference 4). MIL-STD-1530 and MIL-A-87221 contain all the suggested tasks and requirements, with supporting guidance and rationale, needed for the most comprehensive ASIP necessary for airframe development. Integration and tailoring of these recommendations to a specific system is accomplished by the generation of and adherence to an ASIP Master Plan.

The standard and specification are tailored by modifying the scope of tasks and requirements to an appropriate level for the airframe being developed. The "fill in the blank" format of MIL-A-87221 allows for tailoring of requirements to the specific needs of a system, giving the Air Force and the contractor flexibility from the baseline structural requirements (the previous MIL-A-008860 series) while meeting system objectives. The result of the tailoring process, not a set of predetermined rigid requirements, defines the structural design and certification requirements for a particular system. The whole process and its results are subject to Air Force review and approval.

Static Strength

Structural design is governed by a myriad of factors, margins, and material property values or allowables. For strength purposes, we will consider the uncertainty factor, material allowables or property values, and margin of safety.

All structure must be designed to sustain limit load without detrimental permanent *deformation and ultimate load without rupture. These conditions are verified by* analysis and test. The limit load is the maximum load the vehicle is expected to see in its lifetime, or the maximum point design load condition, whichever is greater. The ultimate load is obtained my multiplying the limit load times the uncertainty factor (formerly known as the factor of safety) which accounts for variations in manufacture, defects not assumed in analysis but present in the structure, design load exceedances and other uncertainties of design, manufacture, and operation. The uncertainty factor is traditionally 1.5 for manned vehicles and unmanned vehicles in the vicinity of a manned carrier, and 1.25 for unmanned vehicles in free flight. The

margin of safety calculated during strength analysis should not be less than zero under these conditions. A component whose failure would cause loss of the vehicle is usually designed using A or S material property values, as found in MIL-HDBK-5 (Reference 5). Other components may be designed with B allowables. An A allowable is the strength value which will be exceeded by 99 percent of the population with a 95 percent confidence level. A B allowable is the strength value which will be exceeded by 90 percent of the population with a 95 percent confidence level. There is no statistical significance to an S value.

Durability

The objective of the durability design requirements is to ensure that the economic life of the airframe is greater than the design life of the system. The economic life is that point in time at which the degradation of the structure due to fatigue cracking, corrosion, and wear has reached a point such that it is more economical to replace the structure than to repair the damage. To verify that the durability requirements have been satisfied, both analysis and test are required. The current accepted analysis approach is to assume that each structural component contains inherent small defects (a .010 inch (.254 mm) radius corner flaw or equivalent) and then to show through fracture mechanics analysis techniques that these flaws will not grow to a size that would necessitate repair or cause functional impairment within the design life of the structure. The test is performed on an average production airframe without any induced flaws, and presumably with less severe flaws than those assumed in analysis. The design is usually analyzed and tested to twice the design life to cover scatter in initial flaw sizes and material crack growth rates. Alternate analytical procedures are employed for both high strength steel and composite structures, but the basic design requirement is material independent. Design development and full scale structural testing is required to verify the durability analysis and to uncover any design deficiencies prior to production. The durability requirements apply to all primary and secondary structure.

Damage Tolerance

All safety of flight structure must satisfy damage tolerance requirements which state that the structure shall maintain adequate residual strength in the presence of material, manufacturing, and processing defects, in addition to service induced damage until these defects can be detected and repaired during periodic scheduled inspections. Current guidance specifies that all safety of flight structure that is not designed as fail-safe must be designed such that no in-service inspections are required. For fail-safe structure, inspections can be scheduled based on the length of time that the structure can safely fly with a failed primary structural member. As with the durability requirements, fracture mechanics analysis procedures are employed and design development and full scale tests are required. Initial flaw sizes that are assumed to exist in the structure are determined through an assessment of the nondestructive inspection technique employed for each component. Traditional flaw sizes have been a .050 inch (1.27 mm) radius corner crack or equivalent. The test article has defects introduced into areas shown to be critical by analysis. The test is successful when the analytical predictions are verified.

Materials Characterization

ASIP requires that all material properties required in design be taken from MIL-HDBK-5, or that new materials use properties developed to its requirements. The characterization process begins with a material screening procedure, evaluating the candidate materials against the design environment for the specific application. It ends when final material properties that meet MIL-HDBK-5 requirements are obtained, including verification of the properties in the final product form as necessary.

Reference 3 provides guidance in material property data base development prior to and during early FSD. When developing a product form such as a casting, with properties unique to part configuration, attention must be paid to design data development. The design of components using preliminary data can pose a significant program risk that must be considered when constructing the ASIP Master Plan. If preliminary data proves to be optimistic, a back up material selection or component redesign may be required, with its attendant cost and schedule impact.

CASTING PECULIAR REQUIREMENTS

The treatment of cast and wrought products is very similar. The most significant difference is the analysis of design data and its relationship to the production article. Extreme care must be taken to insure the consistency of the design properties in the production article throughout the production run. In addition to the procedures discussed here, all the other ASIP aspects must be satisfied, including the need for a Durability and Damage Tolerance Control Plan, as described by Reference 6. The combination of ASIP tasks, specification design and certification criteria, and the MIL-HDBK-5 requirements for new materials must be satisfied. This goal is made particularly difficult to achieve by the nature of the cast product.

Static Strength

Two methods have been used for the design and analysis of castings. The first is a traditional casting factor approach which accounts for the variability of mechanical

properties. The second is intended to put castings on the same basis as wrought metallic product forms. Both methods require the destructive inspection and test of a first casting, with continued destructive inspection and test of production castings on a sampling basis, as well as the test of prolongations from each casting.

The first, the casting factor method, requires the use of S values from MIL-HDBK-5, or as guaranteed by the foundry for materials not found in MIL-HDBK-5. This is used with typical casting grade alloys, such as the A357 aluminum alloy included in MIL-C-21180 (Reference 7). The analysis must maintain a minimum margin of safety of 0.33 (equivalent to a casting factor of 1.33), on both limit and ultimate calculations.

The second, a "casting factor free" method, has only recently been used in a single specifically approved application on a critical component. This approach is only available to the highest grade of casting practice, as exemplified by the D357 aluminum alloy covered by the AMS 4241 specification (Reference 8), and is currently approved only on a case by case basis subject to thorough scrutiny by the Air Force. Reference 1 describes this method. Such an approach requires the use of allowables developed to the requirements of MIL-HDBK-5 in conjunction with a tighter materials specification to insure consistent product quality throughout production. The allowables approved for this application were approved for this one application only and their verification for other configurations and final publication in MIL-HDBK-5 is currently awaiting a thorough analysis of production quality control data from the F-16 inlet duct project.

Whether using published MIL-HDBK-5 allowables or allowables developed to MIL-HDBK-5 criteria it is necessary to insure that the proposed casting will fall within the same population data base as the allowables. This procedure requires that a small sampling of data from the proposed casting be tested against the larger sample from which the allowables were derived. If the test indicates that the small sample came from the same population as the large sample, then the existing allowables may be used. This reduces the data requirements and development time by taking advantage of previously generated data bases.

The requirements of MIL-HDBK-5 for new cast materials have been applied as follows:

Data analysis requirements demand the test of a quantity of specimens excised from production configuration castings and use of the data to develop allowables by the procedures described in Chapter Nine of MIL-HDBK-5. One hundred specimens are required for data exhibiting a Normal or Weibull distribution. Three hundred specimens are required for data which fall in a non-parametric distribution.

Material and process definition through the use of an industry standard material and process specification that includes strict chemistry controls, typically tighter than those in the currently available MIL-C-21180 for aluminum castings, and a requirement for metallographic inspection. Grain size, dendritic arm spacing, or some other key microstructural feature relevant to the processing history and resultant properties of the casting must be observed and correlated to the properties of interest.

Also necessary is an agreement between foundry and airplane manufacturer that includes an accept/reject criteria based upon the prolongation test results and the corresponding metallographic inspections being used to verify the properties within each casting.

Durability and Damage Tolerance

While basic fracture mechanics based analytical techniques can be employed to satisfy both the durability and damage tolerance requirements for castings, additional consideration must be given to their unique properties. The variation of crack growth rate and fracture toughness properties throughout the component is the most difficult problem to address. This problem usually requires that the material properties used for design are verified by testing specimens that are removed from the specific critical locations in the actual cast part when it becomes available. Because the likelihood for porosity or particulate contamination is much greater in castings than in most wrought products, embedded defects must also be considered in the durability and damage tolerance analysis and testing. The verification of the nondestructive inspection capability, both during manufacture and in-service, for these types of defects must be addressed during development. A final problem that should be considered also deals with the inspectability of the component. The use of "as-cast" surfaces severely restricts the inspectability of the component and if the component is safety of flight critical, may necessitate the use of an extremely large initial flaw size assumption (much larger than the usual .050 inch (1.27 mm) radius corner flaw) for damage tolerance analysis and test. These issues are currently being addressed by Air Force research programs (Reference 9).

Typical average material crack growth rate properties are employed in durability and damage tolerance calculations for both wrought and cast components, but for a casting these typical properties may only apply to a specific location within the casting. Vendor guaranteed minimum fracture toughness values are generally required for safety of flight critical components. The guarantee of fracture toughness should be based upon an improved material specification, metallographic inspection, and the test of prolongations, and be subject to an agreement between foundry and manufacturer much like what has been described for strength verification.

DESIGN CONSIDERATIONS

The detail design process generally makes use of nominal dimensions for the stress analysis of wrought products. Unfortunately, cast products may have larger tolerances than are typical of wrought forms. As a result, attention must be paid to the dimensions used in analysis and the analyst must consider the effects of minimum dimensions on stress levels for critical areas, and subsequent fatigue and fracture behavior.

The strength properties of wrought aluminum products are better than those of comparable cast products. Any weight advantage for cast materials over wrought materials will come from the reduction of fasteners and joint overlaps and not reduction in cross sectional area. Consequently, the maximum advantages of castings are in the reduction of part counts and complex machining operations, thereby reducing costs. The option of factor-free casting design offers the best use of this advantage with minimum weight penalty.

When considering an application with both strength and fatigue and fracture requirements, the competing effects of grain size must be addressed. A finer grain size will enhance strength, while a coarser grain size may improve crack growth and fracture toughness properties. Consequently, grain size becomes an important consideration in relation to normally applied strength and fracture values.

Care must be exercised when zoning the casting to ensure that only the areas that require close property control receive the highest class rating. The positioning of gates, risers, and chills as well as the part configuration, affects the properties achievable in any particular area of the casting. The best properties are not achievable in all areas of the casting, and the designer should be selective in zoning the casting.

The lack of certainty in a casting's fracture mechanics properties generally necessitates a very conservative initial design approach to satisfy the durability and damage tolerance requirements. This conservatism is reinforced by the very low guaranteed minimum fracture toughness values currently offered by the casting vendors. However, this required conservatism may not have a significant impact on the overall cost or weight of the casting because it only affects localized design details.

The use of 'as-cast' surfaces severely restricts the inspectability of the component and may necessitate the use of an extremely large initial flaw size assumption if the component is safety of flight critical. To qualify the use of smaller flaw sizes, the machining of critical areas of a casting to enhance its inspectability may be required. This could have a significant cost impact and should be considered early in the design process.

The development of material properties must be compatible with the system development schedule. It is ideal to have final design properties prior to the design of a casting. The nature of the casting prohibits this until a sufficient data base is accumulated that will allow highly accurate prediction of properties. The current status of this data base suggests that the design of critical castings must begin early enough to allow the development or verification of design allowables prior to design finalization. If this is not done, conservative properties should be used to assure that the final product will meet qualification requirements without need for redesign. In any case, a "building block" approach must be taken that assures the presence of the desired properties in each successive step of the development process, from material screening to the final part qualification.

CONCLUSION

ASIP requirements provide a performance oriented structure development program within which any material can be used so long as it meets the design and qualification criteria. This is a comprehensive program that will assure development of a qualified product if properly applied. A key element of the program is the requirement that material allowables be developed in accordance with MIL-HDBK-5 criteria.

Satisfying MIL-HDBK-5 criteria is more involved than testing of 100 specimens. It requires validation of material properties over a production run for a single component, and requires the material be used in several more applications before accurate prediction of and confidence in allowables is achieved. There are statistical measures that must be made of the data prior to acceptance. We would rather not publish allowables at all than to publish and later withdraw the allowables because they could not be achieved in practice. Inclusion of a material in MIL-HDBK-5 is a certain indication that the product has matured to the point where properties are calculable and consistent. The development of material allowables for the cast product form has so far proven to be a strenuous exercise of foundry practice and data analysis, and an exercise that is yet to be completed.

The improvement of casting technology in recent years has encouraged the use of castings without a casting factor. The procedures outlined here describe the mechanism used to allow approval of a casting factor free design for one case. It is being considered a valid approach for other applications on an approval basis. This option is only practical for the highest grade of premium casting and requires Air

Force approval given only on a part by part basis. The data base does not support a blanket approval approach at this time. The development of improved material specifications, nondestructive inspection techniques, and publication of MIL-HDBK-5 allowables are required before there is equivalent treatment of cast and wrought product forms in the certification process.

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FIGURE 1. QUALIFICATION PROCESS

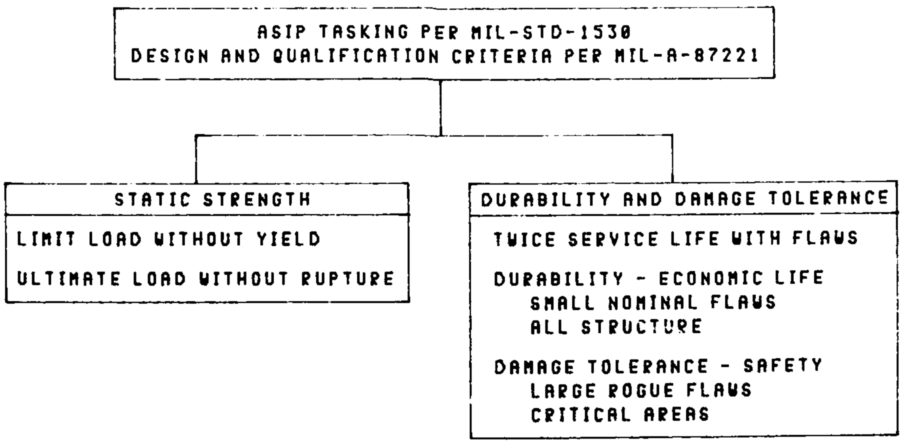

FIGURE 2. CASTING QUALIFICATION PROCESS STATIC STRENGTH

BASIC CASTING REQUIREMENTS

DESTRUCTIVE TEST & INSPECTION OF FIRST CASTING
CONTINUED DESTRUCTION ON A SAMPLING BASIS
TEST PROLONGATIONS FROM EACH CASTING

WITH CASTING FACTOR

USE S STRENGTH VALUES
MINIMUM MARGIN: 0.33

WITHOUT CASTING FACTOR - 'CASTING FACTOR FREE'

USE MIL-HDBK-5 APPROVED A & B ALLOWABLES
INDUSTRY STANDARD MATERIAL SPECIFICATION
STRICT CHEMISTRY CONTROLS
METALLOGRAPHIC INSPECTION
ACCEPT/REJECT CRITERIA DEFINED AND AGREED TO BETWEEN FOUNDRY AND AIRPLANE MANUFACTURER

FIGURE 3. CASTING QUALIFICATION PROCESS DURABILITY AND DAMAGE TOLERANCE

VERIFY FRACTURE PROPERTIES IN PRODUCTION CONFIGURATION

ASSUME EMBEDDED DEFECTS ARE PRESENT

VERIFY NONDESTRUCTIVE INSPECTION (NDI) FOR EMBEDDED DEFECTS

VERIFY NDI FOR AS-CAST SURFACES

DURABILITY FLAW ASSUMPTIONS EQUIVALENT TO WROUGHT FORMS

DAMAGE TOLERANCE FLAW ASSUMPTIONS DEPENDENT ON NDI CAPABILITY

CRITICAL GUARANTEED FRACTURE PROPERTIES MONITORED BY SAME METHOD AS STRENGTH PROPERTIES

LES "CASTINGS FACTORS" IMPOSES PAR LA REGLEMENTATION FRANCAISE POUR LES PIECES DE FONDERIE UTILISEES DANS LES AVIONS MILITAIRES

par

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1 - INTRODUCTION

Le "PANEL STRUCTURES ET MATERIAUX" de l'AGARD mène depuis un certain temps une réflexion sur les pièces de fonderie et s'interroge notamment sur les freins qui limitent leur emploi dans les constructions aéronautiques.

Cette interrogation est d'autant plus pertinente que la fonderie a fait, ces dernières années, d'importants progrès et qu'une exploitation plus large de ses possibilités permettrait vraisemblablement de concevoir et de réaliser des éléments de structure à moindre coût.

Un des principaux freins semble être l'existence de marges de dimensionnement supplémentaires - les "CASTING FACTORS" imposés aux pièces de fonderie par la réglementation en vigueur.

Afin de faire le point sur cette question et comme il me l'a été demandé dans le cadre des travaux de cette table ronde, je vais :

- brosser un tableau des "CASTING FACTORS" imposés par la réglementation française aux pièces de fonderie employées dans les avions militaires,

- suggérer quelques réflexions permettant de faire évoluer la situation.

2 - LES "CASTING FACTORS"

2.1. Normes applicables

Les avions militaires et plus généralement les avions pilotés soumis au contrôle de l'Etat français, doivent satisfaire aux exigences imposées par la réglementation AIR édictée par la **Direction des Constructions Aéronautiques** du Ministère de la Défense.

La résistance structurale est traitée par la Norme **AIR 2004/E,** édition n°6 du 8 mars 1979, et intitulée "Résistance des avions"; le § 1.3.3.2.2 de cette norme impose des marges de résistance (CASTING-FACTORS) à appliquer aux pièces de fonderie.

Les pièces de fonderie sont traitées par la Norme **AIR 3380/C,** édition n°4 du 3 novembre 1975, mise à jour n°1 du 22 mai 1987, intitulée "Instruction relative aux pièces de fonderie en alliages d'aluminium et de magnésium".

2.2. Tableau résumé des exigences demandées.

Le tableau n° 1 résume les exigences demandées par cette réglementation AIR pour les pièces de fonderie :

a) Classification (colonnes 1 et 2)

La Norme AIR 3380/C définit 3 classes de sévérité de contrôle reliées directement à la fonction de la pièce et deux sous - classes tenant compte de la difficulté de réalisation de celle-ci.

La fonction de la pièce sera :

- **VITALE** : Si sa défaillance en service (en vol ou au sol) risque d'entrainer la destruction de l'appareil ou l'impossibilité de remplir la mission.

- **IMPORTANTE** : Si sa fonction n'est pas vitale, mais sa défaillance risque d'entraîner une perturbation majeure dans l'exploitation du matériel.

- **SECONDAIRE** : Si sa fonction n'est ni vitale, ni importante, c'est-à-dire si sa défaillance ne risque pas d'entraîner de perturbation notable dans l'exploitation du matériel.

b) **"CASTING FACTORS"** (colonne 3)

La Norme AIR 2004/E, dans son § 1.3.3.2.2, impose aux pièces vitales de fonderie", en alliage d'aluminium ou de magnésium, une marge minimale de :

. 10 % par rapport aux charges limites,
. 25 % par rapport aux charges extrêmes,

soit un "CASTING FACTOR", vis-à-vis des charges extrêmes, de 1,25.

Pour les pièces à fonctions importantes ou secondaires, aucun "CASTING FACTOR" n'est exigé.

Pour les pièces de fonderie en titane, en aciers ou en alliages réfractaires, il n'existe pas de réglementation AIR spécifique et donc de "CASTING FACTORS" définis.

Les marges éventuellement prises pour ces pièces résultent de la démonstration de la tenue mécanique de la pièce qui a été faite et présentée aux Services Officiels pour répondre aux exigences réglementaires globales du matériel.

c) **Contrôles associés** (colonne n° 4)

Pour avoir une idée précise du niveau de sécurité demandé aux pièces de fonderie, ce tableau doit être complété par les contrôles exigés. Les plus importants d'entre-eux figurent d'une manière résumée dans la dernière colonne du tableau. (En annexe, on trouvera un tableau complet des contrôles imposés par la Norme AIR 3380/C).

En plus des contrôles exigés et afin de maintenir dans le temps le niveau de qualité des pièces produites, la Norme AIR 3380/C impose pour :

- les pièces vitales :

  . l'établissement d'une "**fiche d'essais**" consignant toutes les exigences du client en matière de contrôles et d'essais et précisant les résultats à obtenir et leur interprétation,

  . l'établissement d'une "**fiche de fabrication**" où sont consignés tous les paramètres du processus de fabrication et de contrôle qui concourent au niveau de qualité des pièces et à la reproductibilité de ce niveau dans le temps.

Ce processus de fabrication est figé et ne doit pas être modifié unilatéralement par le fondeur.

- les pièces importantes :

  . l'établissement de la **fiche d'essais** seulement.

Au niveau des contrôles, on notera en particulier les exigences suivantes :

- pour les pièces vitales

  . un contrôle de santé par radiographie sur 100 % des pièces, avec des critères d'acceptation sévères aussi bien pour les zones désignées (les plus travaillantes) que pour les zones courantes,

  . une mesure des caractéristiques mécaniques :

    - sur éprouvettes de dissection, avec une fréquence de dissection d'une pièce par lot,

    - sur éprouvettes attenantes (à la pièce et représentatives des zones critiques) à 100 %.

- pour les pièces importantes et secondaires

Des contrôles de même type, mais leur fréquence (notamment dans les zones non désignées) sera moindre et les critères d'acceptation seront plus larges.

3. REFLEXIONS

Pour terminer cette présentation, je souhaiterais vous livrer quelques réflexions personnelles.

3.1. - En premier lieu, on constate, depuis ces dix dernières années, une évolution importante dans le domaine de la fonderie.

a) Au niveau technique

On constate de plus en plus la mise en place de procédés nouveaux ou améliorés qui intégrent plusieurs techniques de fonderie traditionnelles en associant, en exploitant les avantages et en minimisant les inconvénients de chacunes d'elles. Par exemple, le moulage" basse pression" des alliages d'aluminium associé à des techniques de moules en sable fortement refroidis (s'apparentant au moulage coquille pour améliorer les caractéristiques mécaniques) et complété partiellement par des techniques de modèle à la "cire perdue" (pour l'amélioration de la précision géométrique et de la finesse des formes réalisables) ouvre d'intéressantes perspectives à la fonderie de qualité pour les usages aéronautiques.

Ces procédés permettent de réduire les minima technologiques habituels des pièces de fonderie notamment en ce qui concerne les épaisseurs. Ainsi, il est maintenant possible d'obtenir des épaisseurs de parois ou de voile de grande surface de l'ordre de 1 à 2 mm avec des caractéristiques mécaniques et une santé interne d'un haut niveau de qualité.

Cette réduction des minima technologiques accentue l'intérêt de réduire les "CASTING-FACTORS" qui, jusqu'à présent, n'avait qu'une influence limitée sur la masse des pièces dans la mesure où une grande partie de celles-ci se trouvait ipso-facto surdimensionnée pour des raisons technologiques.

b) Au niveau de la maîtrise de la qualité

La conception d'une pièce de fonderie qui exploite aux mieux les possibilités techniques des nouveaux procédés impose obligatoirement une coopération étroite entre le client et le fondeur. Une telle coopération conduira à une meilleure optimisation de la pièce et sera valorisante pour les deux partenaires. Ce type de démarche a, par ailleurs, toujours été très favorable à la qualité des pièces obtenues.

L'automatisation des nouveaux procédés de fonderie (exemple: fonderie basse pression) qui par nature nécessite la mesure, l'exploitation et donc le contrôle de nombreux paramètres du processus de fabrication pour piloter le fonctionnement de l'installation est un facteur important d'amélioration du niveau de qualité et de sa reproductibilité dans le temps.

La sélection des fondeurs et la généralisation de l'application des concepts "d'Assurance Qualité" avec les procédures, les moyens et l'état d'esprit qui y sont attachés constituent également des facteurs importants d'amélioration de la qualité et de la fiabilité que l'on est en droit d'attendre des pièces de fonderie pour usages aéronautiques.

3.2. - En second lieu, il me paraît souhaitable de s'interroger sur les implications techniques et économiques des "CASTING-FACTORS".

En France et pour les pièces de fonderie destinées aux avions militaires, je rappellerai que le "CASTING-FACTOR" ne s'applique qu'aux pièces vitales et il faut remarquer que celui-ci ne concerne, généralement, qu'une partie de la pièce, l'autre étant dimensionnée soit par des minima technologiques de la fonderie soit par des impératifs de rigidité. Ainsi donc, supprimer le "CASTING-FACTOR" de 25 % ne réduira pas pour autant la masse de la pièce de 25 % mais seulement de quelques pourcent et, au niveau global de la structure avion, l'écart de masse sera relativement marginale.

Par ailleurs, les pièces de fonderie ne sont pas seules à être concernées par des marges de sécurité supplémentaires. Les liaisons principales, réalisées généralement à partir de demi-produits corroyés, et les éléments fréquemment démontables doivent être, d'après la Norme AIR 2004/E, surdimensionnés avec des coefficients de majoration de 15 à 25 % mais ces marges peuvent être réduites, voire supprimées, si une justification par essais statiques et dynamiques parfaitement représentatifs a pu être effectuée.

- L'existence des "CASTING-FACTORS" permet d'avoir une justification allégée de la tenue structurale des pièces de fonderie par rapport à celle qui doit être faite pour les pièces ne présentant pas de marges réglementaires.

- Supprimer le "CASTING-FACTOR" suppose donc une justification statique et dynamique complète de la pièce de fonderie. Le coût complémentaire de cette justification sera important et devra être pris en compte dans le bilan économique.

A condition que des bases statistiques puissent être établies :

. la justification statique ne posera pas de problème particulier; elle se fera par un essai global et une dissection de pièce (déjà prévue dans la norme AIR 3380/C),

. la justification en fatigue sera déjà beaucoup plus délicate et onéreuse; un essai représentatif de fatigue sera nécessaire,

. la justification en tolérance aux dommages, notamment pour les avions de transport, sera très complexe et même parfois impossible; par ailleurs, la prise en compte des défauts de fonderie tolérables conduira vraisemblablement à des marges de surdimensionnement comparables à celles résultant des "CASTING-FACTORS" actuels.

En fin de compte, le problème du "CASTING-FACTORS" se pose en terme de bilan technico-économique.

Si la pièce est dimensionnée avec un "CASTING-FACTOR", sa justification sera simple et d'un coût modéré. La solution fonderie sera attractive en terme de coût en contre partie d'une légère pénalité de masse pouvant, dans bien des cas, être compensée par une meilleure exploitation des possibilités d'intégration structurale permise par la fonderie.

Si la pièce n'est pas dimensionnée avec un "CASTING-FACTOR", sa justification sera complexe et risque d'être très longue et onéreuse. Le coût global sera proche de celui des autres technologies mais l'exploitation rationnelle des possibilités de fonderie doit également pouvoir conduire à des solutions technico-économiques intéressantes notamment lorsqu'une pièce de fonderie remplace toute une structure d'éléments assemblés.

4. - CONCLUSIONS

Compte tenu de ce qui vient d'être présenté il me semble possible d'assouplir les modalités d'application des "CASTING-FACTORS". Ils peuvent même être supprimés si l'avionneur est capable de réaliser et de présenter aux autorités officielles une justification complète de son élément de stucture réalisé en fonderie. Mais cette justification devra se faire par analyse qui, elle-même, devra s'appuyer sur des essais statiques, de fatigue et de propagation des dommages représentatifs de l'utilisation de cet élément.

- TABLEAU 1 -

CASTING - FACTORS

AIR 3380/C		AIR 2004/E	AIR 3380/C
FONCTION DE LA PIECE	CLASSE DE SEVERITE	CASTING-FACTORS	PRINCIPAUX CONTROLES EXIGES
VITALE	1	1,25	- Fiche d'essais - Fiche de fabrication --------- Santé : Radiographies (Rx) 100 % des pièces Zones désignées et zones courantes Caractéristiques mécaniques (CM) : - sur pièces disséquées une par lot naturel ou artificiel - sur éprouvettes attenantes 100 %
IMPORTANTE	2	1	Fiche d'essais --------- Santé : Rx 100 % pour zones désignées 50 % puis 20 % pour zones courantes (1) Caractéristiques mécaniques - sur pièces disséquées 1 par lot (1) - 20 % sur éprouvette attenante
SECONDAIRE	3	1	Santé : Rx 10 % des pièces (1) Caractéristiques mécaniques - une éprouvette de caractérisation par coulée

(1) allègement si la pièce est de réalisation facile ou si la qualité de fabrication a été statistiquement établie.

- ANNEXE -

MINISTÈRE DE LA DÉFENSE

INSTRUCTION relative aux pièces de fonderie en alliages d'aluminium et de magnésium	3 Novembre 1975	AIR	3380/C 16

Tableau récapitulatif des conditions de réception des pièces de fonderie en alliages d'aluminium et de magnésium

	CLASSE DE SÉVÉRITÉ de contrôle	SOUS-CLASSE DE CONTRÔLE	LOTISSEMENT	NOMBRE D'ANALYSES CHIMIQUES par coulée	DÉFAUTS EXTERNES	CONTROLE DIMENSIONNEL – Cotes principales	CONTROLE DIMENSIONNEL – Cotes générales	DISSECTION – Mode de lotissement	DISSECTION – Fréquence	ESSAIS SUR ÉPROUVETTES e.a. : éprouvette attenante e.c. : éprouvette de caractérisation	DÉFAUTS INTERNES – RADIOGRAPHIE – Fréquence		DÉFAUTS INTERNES – RADIOGRAPHIE – Degré de sévérité	TEXTURE	DURETÉ SAUF ALLIAGE de Mg	ESSAI DE PRESSION (pièce classée étanche)
Paragr. de référ.	3.3		5.2	4.1	4.2	4.3		4.5.3.2		4.5.3.1, 4.5.3.3	4.4		4.4.1.2	4.6	4.5.5	4.5.6
Pièce VITALE	1	0	Lots naturels ou artificiels (§ 5.21 ou 5.24)	1	100 %	100 %	3 pièces par lot pour moulage sable, 1 pièce par lot pour moulage coquille	Lot naturel	1 par lot	e.a. : 100 %	Zone désignée (Zd)	100 %	A	Sur pièce disséquée et sur éprouvettes attenantes	100 %	100 %
								Lot artificiel	10•, 25•, 50• et ensuite par tranche de 25		Zone courante (Zc)	100 %	B			
	1	1	Idem	1	100 %	100 %		Lot naturel	1 par lot	e.a. : 100 % (¹)	Zone désignée (Zd)	100 %	A	Idem	100 %	100 %
								Lot artificiel	10•, 25•, 50• et ensuite par tranche de 50		Zone courante (Zc)	100 %	B			
Pièce IMPORTANTE	2	0	Idem	1	100 %	100 %		Lot naturel	1 par lot	e.a. : 20 % (²)	1re à 50e pièce	> 50e		Idem	100 %	100 % (⁴)
								Lot artificiel	10•, 25•, 50• et ensuite par tranche de 50		Zd 100 %	Zd 100 %	B			
											Zc 50 %	Zc 20 %	C			
	2	1	Idem	1	100 %	100 %		Lot naturel	1 par lot	e.a. : 10 % (³)	1re à 50e pièce	> 50e		Idem	100 %	100 % (⁴)
								Lot artificiel	10•, 25•, 50• et ensuite par tranche de 50		Zd 100 %	Zd 100 %	B			
											Zc 20 %	Zc 10 % avec min. de 1 par lot	C			
Pièce SECONDAIRE	3	0	Lots naturels ou artificiels admis en lot mixte (§ 5.2.1, 5.2.2, 5.2.3, 5.2.4)	1	100 %	100 %		Tous types de lots	Pas de dissection. Éventuel. 1 par tranche de 100	e.c. : 1 éprouvette par coulée	1re à 50e	> 50e			100 %	Suivant demande (⁶)
											10 %	3 %	D			
	3	1	Idem	1	100 %	100 %		Tous types de lots							10 %	

(1) Allègement possible e.a. : 50 %.
(2) Allègement possible e.a. : 10 % avec min. de 1 éprouvette dans le cas de T.T. à l'unité.
(3) Allègement possible e.a. : 5 % avec min. de 1 éprouvette dans le cas de T.T. à l'unité.
(4) Possibilité d'allègement du pourcentage de contrôle radiographique : Zd : 50 %; Zc : néant.
(5) Possibilité de suppression de l'examen radiographique.
(6) Possibilité de suppression de l'examen radiographique.

CASTING AIRWORTHINESS JOINT EUROPEAN CIVIL AUTHORITIES VIEW-POINT

by

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ABSTRACT.

After a short introduction on the European regulation, JAR 25 (JOINT AIRWORTHINESS REQUIREMENTS), the general certification procedures are described : static, fatigue, damage tolerance, manufacturing.

Particular application to casting is discussed, particularly extra factors and damage tolerance evaluation.

In conclusion a general overview of civil airworthiness authorities is given.

1.- THE JAR 25 REGULATION.

In the past, each European country had its own requirement either national (BCAR in UK, Air 2051 in France) or based on US FAR 25 amended by special conditions. In 1974, some European countries joined together to establish a common civil airworthiness regulation, JAR 25 (Joint Airworthiness Requirement). It was based on US FAR 25 and some specialized Study Groups were set up to introduce modifications in accordance with European practices. The JAR Structures Study Group (SSG) is in charge of parts C and D related to structures, materials, design and manufacturing.

Today, members of authorities and manufacturers from Belgium, Germany, France, Italy, Netherlands, U.K. and Sweden are working together in SSG.

Since 1980 all twelve participating JAR countries have adopted JAR 25 as common basis for certifying civil aircraft (except light airplanes, sailplanes and helicopters). Engine parts also are not covered in JAR 25. So this paper deals with certification procedure of structural parts by JAR 25, with special application to castings and is not applicable to engine structures.

2.- STRUCTURAL CERTIFICATION.

Any structural stressed part must be certified according to static and fatigue and/or damage tolerance requirement (Pl. 1). For static strength justification analysis and/or tests are allowed, hence the need of allowables based on A or B statistical values. A safety factor of 1,5 is usually applied to limit loads to obtain ultimate loads, i.e. the minimum required strength level (except when special extra factors are needed as for castings).

For fatigue justification of safe-life parts, evaluation by analysis and/or tests should demonstrate that no catastrophic failure will happen during the operational life of the part. European practice calls for a fatigue test using a scatter factor (3 to 5 or sometimes more).

For damage tolerance justification, the rule is well known : starting from a detectable damage size, evaluate crack propagation under service loads to a critical length defined as giving a failure under limit load. The result, divided by a safety factor will give the inspection interval.

It must be added that in-service repairs should comply with these requirements : the repaired part must have its initial strength (ultimate load) and have equal fatigue or damage tolerance properties.

In addition material properties and design and manufacturing process should be taken into account and quality control must show that all parts are within the demonstrated values (Pl. 2 and 3).

3.- APPLICATION TO CASTINGS.

Structural parts manufactured by casting processes must comply with these general rules.

3.1 Static strength.

The main point is the extra factor added by § 619. This factor is needed "for parts whose strength is uncertain or subject to uncertainties in manufacturing process or inspection methods". The value of this factor should be given by § 621 but JAR 25.621 says : "the approved national standards of the participants are accepted by the authorities as alternative to FAR 25.621". The value of the casting factor depends on the criticality of the part (see Pl.4). The old U.K regulation (B.C.A.R.) added the difference between simple or complex parts. A synthesis on the value of the factor for FAR 25 (basis for most European countries) and BCAR is shown in plates 5 and 6.

To summarize the requirement, it can be said that authorities allow casting for parts defined as critical, that the factor is at least 1,25 (except for U.K. with 1,33, but C.A.A. has already accepted 1,25 for an item of the A 320), that three static tests and 100 % NDI by visual, X.ray and magnetic particle or dye penetrant methods are necessary (Plate 7).

The reasons for the factor given in § 619 are mainly the uncertainties in strength due to material variability (and so the difficulties in obtaining allowables based on statistical A or B value), the manufacturing process (size variation, internal defects) and the confidence in NDI to detect internal defects. The eventual deletion or lowering of this factor could only be based on progress made in reducing these uncertainties.

3.2 Fatigue and damage tolerance.

For main structural parts, fatigue and/or damage tolerance evaluation should be made according to § 571. This requirement is summarized in Pl. 8 with the particular problems associated with castings.

If casting are used for safe-life parts, do we need to take into account the manufacturing defects not detected by NDI methods, which could surely give a large scatter on the results ?. In fact, this point would depend on the size of these defects and the analogy with other manufacturing process such as forgings could be of interest.

For damage tolerant parts, the problems would be with the definition of initial cracks, the analysis and tests for crack propagation, the analysis and test for residual strength : confidence in mathematical models due to complex shapes and material properties scatter, representativeness of tests.

4.- CONCLUSION.

The points discussed above give a general overview on structural certification with particular application to castings. In fact, civil authorities do not have much experience with these cast parts to date. In the past, very few castings were used for primary, or even secondary, structures. For example, the only cast part certified on the A 320 is the falp-track fitting.

To conclude, civil authorities are ready to certify primary structural parts made by casting process. They ask for the same level of confidence in safety with cast parts as with parts manufactured by other well known processes. To comply with this, the main points to improve seam to be the knowledge of pertinent allowables, the existence of manufacturing defects, the confidence in NDI methods, the confidence in control to maintain the quality throughout production. The extra factor was introduced to cover these uncertainties and its deletion or reduction could only be based on the improvement in these subjets. But as damage tolerance justification is also needed for critical parts, one can wonder if this requirement would not, in pratice, make a higher static margin necessary.

STRUCTURAL REQUIREMENT (PART C)

STATIC STRENGTH (§ 301, 303, 305, 307)

- NO PERMANENT DEFORMATION UNDER LIMIT LOADS
- ULTIMATE LOADS BY ANALYSIS AND/OR TEST WITH A SAFETY FACTOR OF 1.5

FATIGUE AND DAMAGE TOLERANCE (§ 571, ADVISORY CIRCULAR ACJ 571)

"...PARTS OF STRUCTURE WHICH COULD CONTRIBUTE TO A CATASTROPHIC FAILURE"

- DAMAGE TOLERANCE UNLESS IMPRACTICAL
- FATIGUE, CORROSION, ACCIDENTAL DAMAGES
- FOR SINGLE LOAD PATH ELEMENTS : MATERIAL FLAWS AND MANUFACTURING DEFECTS

PLATE 1

MATERIAL AND DESIGN REQUIREMENT (PART D)

§ 601 - NO HAZARDOUS OR UNRELIABLE DESIGN

§ 603 - SUITABILITY AND DURABILITY OF MATERIALS BASED ON EXPERIENCE AND APPROVED SPECIFICATIONS

§ 605 - FABRICATION METHODS FOR PRIMARY STRUCTURES SOUND AND RELIABLE
- NO MAJOR DEFECT AFTER MANUFACTURE

§ 609 - SUITABLE PROTECTION AGAINST CORROSION, WEATHERING AND ABRASION

§ 611 - ACCESSIBILITY FOR INSPECTION

.../...

PLATE 2

MATERIAL AND DESIGN REQUIREMENT
(FOLLOWING)

§613 - MATERIAL STRENGTH AND PROPERTIES TAKING INTO ACCOUNT :

- TEST ON STATISTICAL VALUES
- VARIATION
- TEMPERATURE
- MANUFACTURING PRACTISES

§615 - SINGLE LOAD PATH : A VALUE
- REDUNDANT LOAD PATH : B VALUE

§619 - SPECIAL FACTORS FOR PARTS WHOSE STRENGTH IS UNCERTAIN OR SUBJECT TO VARIABILITY DUE TO UNCERTAINTIES IN MANUFACTURING PROCESS OR INSPECTION METHODS

§621 - SPECIAL CASTING FACTORS

PLATE 3

CLASSIFICATION OF CASTING

CLASS	DEFINITION
CRITICAL (FAR) CLASS 1 (U.K.) CLASS 1 AND 2 (NETH.)	FAILURE PRECLUDE CONTINUED SAFE FLIGHT AND LANDING OR RESULT IN SERIOUS INJURY TO OCCUPANTS U.K. - SIMPLE (SHAPE, NO CAST DIFFICULT) (18 lb (Mg), 25 lb (Al), 100 lb (Steel) - COMPLEX
NON CRITICAL (FAR) CLASS 2 (U.K.) CLASS 3 (NETH.)	OTHER PARTS PARTS NON INCLUDED IN CLASS 1 OF WITH MORE THAN VISUAL EXAMINATION IS NECESSARY TO ENSURE RELIABILITY
CLASS 3 (U.K.)	ALL OTHER PARTS

PLATE 4

CASTING FACTOR (1)

CLASS	FAR 25 Italy, Germany, France + Netherland	BCAR (U.K.)
CRITICAL CLASS 1 (U.K.)	- C.F. ≥ 1.25 - 100% NDI VISUAL AND X.RAY AND MAGNETIC OR DYE PENETRANT - IF C.F. < 1.5 3 TEST . 1.25 x U.L. . NO DEFORMATION 1.15 x L.L.	SIMPLE (CALCULATIONS BASED ON MINIMUM SPEC. VALUES) - C.F. ≥ 2 (Mg-Al) C.F. ≥ 1.5 (Steel) OR - TEST ON 1 FROM 20 FIRST PARTS C.F. ≥ 1.50 (Mg-Al) C.F. ≥ 1.25 (Steel) OR - TEST ON 3 FROM 20 FIRST C.F. ≥ 1.33 (Mg-Al) C.F. ≥ 1.15 (Steel) COMPLEX - TEST ON 3 FROM 20 FIRST C.F. ≥ 1.33 (Mg-Al) C.F. ≥ 1.15 (Steel)
		NDI 100% X.RAY

PLATE 5

CASTING FACTOR (2)

CLASS	FAR 25 Italy, Germany, France + Netherland	BCAR (U.K.)
NON CRITICAL CLASS 2 (U.K.)	- 1.25 ≤ C.F. < 1.5 100% NDI VISUAL AND X.RAY AND MAGNETIC OR DYE PENETRANT - 1.5 ≤ C.F. < 2 100% NDI VISUAL AND MAGNETIC OR DYE PENETRANT - C.F. ≥ 2 100% NDI VISUAL	NDI VISUAL +

PLATE 6

SYNTHESIS OF MINIMUM STATIC REQUIREMENT

- CASTING ALLOWED FOR CRITICAL PARTS
- CASTING FACTOR AT LEAST 1.25
- 3 STATIC TEST TO 1.25 x U.L.
- 100% NDI BY VISUAL
  AND X.RAY
  AND MAGNETIC OR DYE PENETRANT

PLATE 7

FATIGUE AND DAMAGE TOLERANCE

- NECESSARY FOR CRITICAL (OR CLASS 1) PARTS

$$a_0 \longrightarrow a_c$$

ΔN ⟶ INSPECTION INTERNAL

- DEFINITION OF INITIAL SIZE a_0

  FATIGUE / CORROSION / ACCIDENTAL ⟶ COULD BE SIMILAR TO CONVENTIONAL PARTS (EXTERNAL DAMAGES)

  MATERIAL FLAW / MANUFACTURING DEFECT ⟶ TAKEN INTO ACCOUNT ONLY FOR SINGLE LOAD PATH ELEMENT

  ⟶ VALUE BASED ON NDI MINIMUM SIZE DETECTION

- EVALUATION OF CRACK PROPAGATION
  + CALCULATION : MATHEMATICAL MODELS
  + TEST : ARTIFICIAL INITIAL DAMAGES
- EVALUATION OF RESIDUAL STRENGTH
  + CALCULATION : ALLOWABLES FOR KC
  + TEST
- IN SERVICE INSPECTION

  NDI METHODS TO BE DEFINED FOR ASSEMBLED PARTS TO GIVE GOOD CONFIDENCE ON DETECTION

PLATE 8

ROYAL AEROSPACE ESTABLISHMENT— NO PLACE FOR A CASTINGS FACTOR

by

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SUMMARY

The structural design and airworthiness requirements for UK military aircraft are published in DEF STAN 00-970. Once a cast material (and the associated process) has been approved it is treated like any other material; there is no "castings factor".

This note outlines acceptable procedures for the certification of advanced castings for use in the primary structure of aeroplanes and helicopters.

1 INTRODUCTION

In structural terms, a successful aircraft must have just sufficient strength and stiffness to enable it to perform the required missions without aeroelastic instability or functional impairment, and to perform these missions over and over again without an appreciable risk of fatigue failure or the imposition of an unreasonable maintenance penalty.

In seeking to achieve these objectives in an increasingly competitive world there has been a new readiness among structural engineers to review the validity of established airworthiness policies. Notably, the static superfactors applied to castings, pressure cabins, single load path structure and composite items have disappeared from DEF STAN 00-970 in recognition of the fact that the uncertainties which they have covered are now addressed directly in such general requirements as those for fatigue, corrosion resistance and the derivation of allowable values of stress using data on variability in strength. Furthermore, the new 'B' basis standard for allowable stresses permits higher values to be used than was normally the case when the traditional minimum specification ('S') values were required. Even the static factor of safety of 1.5 has been brought into question and some relaxation is envisaged in a climate of strict control of permitted loads and increased exploration of structural behaviour in the heretofore largely uncharted region above limit load.

2 THE CERTIFICATION OF CASTINGS

2.1 Materials and Processes

The cornerstone of airworthiness approval by the usual procedures is consistency of product. To this end new castings and processes must be submitted for approval in association with a programme of radiological, mechanical and crack detection tests.

For an entirely new cast material it would be necessary to make a number of castings representing the range of proposed applications in size and complexity. Sufficient castings would need to be made to enable a total of about 15 coupon specimens to be cut representatively from 'difficult' areas and used to measure the strength and variability in each significant failure mode (typically tension compression and shear). If only 15 coupons were used these would need to comprise at least 5 samples from each source of supply and at least 3 'batches' of material from each source (Chapter 200 (General Static Requirements) paragraph 4). Having established this data bank it could then be used both for the derivation of 'B' basis allowables in each failure mode and to provide variability data for the interpretation of tests on particular designs of casting using the same, or a closely similar, material and process.

The authority for approval at all stages would rest with the UK Ministry of Defence

Prepared as a statement of UK military practice for an AGARD Workshop on Castings Airworthiness, Mierlo, Netherlands, 5-6 October 1988.

2.2 Static Strength Certification by Component Tests

The requirement for all structural details, such as castings, is to obtain a 'B' allowable value. There is a separate requirement to show that this is not exceeded at the design ultimate load.

If a casting were reasonably complex, or there was a need to avoid any mass penalty that might be needed to allow for uncertainties in calculations (Chapter 200 paragraphs 4 and 5) then it would be appropriate to test at least two examples of the casting to failure under a close representation of the design loading. Where appropriate, environmental degradation would be reproduced in the test. From examination of the fracture the failure mode would be determined. Reference would then be made to the data bank for the coefficient of variation obtained from the coupon specimens representing the observed failure mode. The mean strength of the small number of castings would then be reduced by a factor (Chapter 200, Table 1, attached) to give the 'B' value for the casting.

2.3 Static Strength Certification by Calculation

If the 'B' allowable for a casting were to be estimated by calculation using 'B' allowables from coupon specimens then an appropriate allowance would need to be made for the added uncertainties.

If the coupon specimens were cut from a similar casting made by the same process then the main consideration would be to allow for uncertainties in the method of calculation. Providing the method had been substantiated for similar types of casting (using Chapter 200, Table 1) then the factor for calculation would not be expected to exceed 1.25 and could be as low as 1.0 if the casting were tested as part of the major static test.

If the coupon specimens were of the 'test bar' type and not therefore representative metallurgically a separate allowance would need to be made to cover this uncertainty. No hard and fast guidance can be given, but it is noteworthy that factors of between about 1.15 and 1.25 have been applied when using 'minimum specification' properties for steel investment castings. The corresponding values for sand castings have been 1.25 for steels and 1.6 for light alloys (Chapter 403 and Leaflet 403/1). These are essentially 'test bar factors' and represent the penalty that must be accepted if more relevant data cannot be provided.

2.4 Fatigue Certification

The amount of effort needed to substantiate the fatigue life (Chapter 201 (General fatigue requirements) and associated leaflets) of any detail depends upon the reserves of fatigue strength that are present. If a part was sized to static or stiffness considerations it might be sufficient to do just a few simple, but conservative, calculations to show that it had an adequate life and then to leave this to be demonstrated during the major fatigue tests. If, on the other hand, these calculations showed the life of the component to be marginal and if refined calculations failed to provide the assurance that was required then a separate component test, or tests, might well be done in advance of the major fatigue test. Such development tests would almost always be done for a non-standard component that was sized by fatigue.

3 CONCLUSION

A 'castings factor' is no longer required when castings are used in the primary structure of UK military aircraft. Static and fatigue certification is obtained by procedures that also apply to wrought materials (including forgings) and to fibre composites.

TABLE 1

Factors by which the Main Strength of Details or Elements must be Reduced to Obtain a 'B' Allowable Value: Where Appropriate Environmental Degradation must be Included in the Tests: These Factors Apply to all Grade A Details and to all Materials

	Estimated population cv from n coupon tests i.e $cv = \frac{\sqrt{\frac{\Sigma(x-\bar{x})^2}{(n-1)}}}{\bar{x}}$	Sample size of coupon tests n, used to estimate population cv in observed failure mode														
		15					30					100 or more				
		Number of element tests N														
		1*	2	3	5	10	1*	2	3	5	10	1*	2	3	5	10
Characteristic cv in observed failure mode	3% or less	1.14	1.11	1.10	1.09	1.08	1.12	1.10	1.09	1.08	1.07	1.10	1.09	1.08	1.07	1.06
	5%	1.26	1.20	1.18	1.16	1.14	1.20	1.17	1.16	1.14	1.13	1.18	1.15	1.14	1.12	1.11
	7.5%	1.37	1.31	1.28	1.26	1.23	1.32	1.27	1.24	1.22	1.20	1.28	1.23	1.21	1.19	1.17
	10%	1.53	1.44	1.40	1.36	1.32	1.45	1.37	1.34	1.31	1.27	1.39	1.32	1.29	1.27	1.24
	15%	1.89	1.74	1.68	1.61	1.55	1.75	1.62	1.57	1.51	1.46	1.63	1.53	1.48	1.44	1.39

* Normally at least 2 tests must be done so that any gross inconsistency is likely to be revealed

Castings, from Theory to Practical Application

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Summary

This article gives a general summary of the state of the experience made by MBB-UT-Bremen with series castings.

From a designer's point of view an attempt is made to make valid statements on the following points:

- Design/Cost Advantages
- Range of Application
- Designer's Confidence in Castings
- Handicap Reduction

These topics are treated in the following chapters:

1. Introduction
2. Advantages of Casting Design
3. Designers' Handicap
4. Conclusion and Prospects

1. Introduction

If the task set to a design engineer is to design a certain airframe component, he has to observe, inter alia, the main criteria as listed herunder and shown in Fig. 1, ensuring:

1. the function of the component
2. the weight of the component as per specification
3. the static and dynamic strength of the component
4. minimum production cost
5. observance of component production schedules

These are the most important criteria which have been listed more or less in the order of priority generally followed by the design engineer. On the basis of these criteria he will decide on the most suitable manufacturing process for this component and then proceed to design the part in question. It is most important that he should consider the application of casting technology already at this stage. We may quote numerous examples of attempts to convert a current production series to casting. It was then found, that this was far from cost-effective: the cost of new tooling, necessary tests and modification costs made any justifiable break-even point impossible. We have realized that the most economic production technology has to be decided upon in the design phase so that can be adapted from the first component on.

Meanwhile, increasing cost pressure which can be observed also in military programs has led to a growing emphasis on this particular problem so that much thought is being devoted to finding cost-effective, manufacturing processes and to enforcing their introduction.

Formerly, it was not possible to use castings for the primary structure but matters have changed following the introduction of the new aluminium cast alloy A357 with its improved strength characteristics.

Mechanical Properties of A357				
		Rp o,2	Rm	A_5 (%)
Investment Casting	Critical Areas	250	310	5
	All Areas	230	290	3
Low Pressure Sand Casting	Critical Areas	280	340	5
	All Areas	240	310	3

Remark: Rp o,2 and Rm in Nmm^{-2} : - for "Investment Casting" up to a thickness of 3 mm

- for "Low Pressure Sand Casting" up to a thickness of 20 mm

With the help of the "WST-M" program (Wirtschaftliche Struktur-Technologien-Metall) (1) that means Economic Structures Technology-Metals. MBB has been in a position to realize at an early stage the high cost potential offered by the use of casting technology for airframe construction.

During and subsequent to this program a series of activities was undertaken with the objective of introducing casting design:

a) Intensification of contacts with foundries.

b) Preparation of a design directive for castings.

c) Preparation of a casting catalogue (collection of castings, presented in tests and figures).

d) Increased invitations to foundry specialists to examine our current productions with the objective of determining potential castings.

e) Extensive introduction of the casting alternative into the comparative cost evaluation within the development programs for new aircraft.

These and other activities have led to a growing awareness of the casting alternative at MBB (see Fig. 2).

On the basis of the "WST-M" program, the first parts to be developed and testet were the Nib and the Intake Floor. These experiences were used in the subsequent A310 and A320 production programs and also for TORNADO, and a large number of cost comparisons were made for a whole series of potential castings. This resulted in the following production items:

- Track I Fitting for Landing Flap, A320 - Fig. 7
- Track II Fitting for Landing Flap, A320 - Fig. 8
- Spoiler Fitting A310 - Fig. 9
- Fitting for MOB Tank, Tornado - Fig. 10

2. Advantages of Casting Design

From the designer's viewpoint, the advantages of casting technology can be subdivided into two main groups (see Fig. 3):

- Design aspects
- Cost reduction aspects

On the basis of our findings, the advantages in the design area can be described as follows:

2.1 Design Aspects:

2.1.1 Realization of Complex Structures:

This covers box-shaped structures which, traditionally can be realized only by means of welded or complicated riveted constructions. Fig. 5, 7 und 8 show examples of such components. These geometrical configurations with two load-bearing ribs crossed by two spar systems are predestinated for casting design.

In addition, casting facilitates: the production of hollows - see Fig. 12, Intake Floor - which, using conventional differential manufacturing procedures, is only achieved by complex milled parts and associated connecting elements.

2.1.2 Integrated Fail-Safe Solution

In a civil transport aircraft, areas (bearings, connections) which lead to the loss of the aircraft in the case of failure have to be provided with a double load path. This leads obviously to complicated milled parts and connecting elements. Track I Fitting, Fig. 13, is a case in point - all these requirements are fully met by an integrated aluminium casting. The second bearing is connected to the bearing proper via a small interspace with ribs. This means that, in case of failure of bearing No. 1, bearing No. 2 will take up the loads.

2.1.3 Run-through of load path

In conventional designs, the design engineer has to decide which of two crossing load paths should be continous and which should be devided and then reconnected by means of splice elements. Casting design is free from such contraints. Casting configurations permit crossing of several uninterruped load paths. This increases the stiffness of the component and additional connecting elements are not necessary.

2.1.4 Increase liberty in design

Casting design leaves the engineer with a wider choice of structural shapes than he could ever attempt in a riveted structure. Some designs meant for installation in reduced spaces may be extremely complicated due to milling radii and legth, rivet pitches and diameters. Since in such highly stressed areas it is in most cases necessary to have a build-up of several milled parts, tolerance problems tend to be considerable and the area has to be permanently reworked. Since this is done during the assembly phase, the costs caused are extremely high. Moreover rework will always destroy the surface protection on the individual parts. The subsequently protection will not reach the same quality level and could leed to premature corrosion. All these drawbacks can be avoided by using a casting instead.

2.1.5 Improved fatigue design

A casting structure can achieve an improved fatigue behaviour owing to casting characteristics such as:

- continuous load paths avoiding splices and splice elements
- soft cross section transitions (a necessity with casting techniques)
- radii can be realized in accordance with fatigue requirements, irrespective of cutter diameters
- none static notches interruptions caused by cross-sectional overlaps

These features were clearly demonstrated by our dynamic tests performed on Nib and Intake Floor components.

2.1.6 Fewer rivet holes

The use of castings considerably reduces the number of connecting parts and there will be fewer rivet holes in a structure. Cracks found on in-service aircraft initiate, in most case, in a rivet hole. Reducing them will make a structure less prone to cracking.

The above-mentioned connections represent an interruption in every flow of forces and will reduce the admissible tension. There will hardly be any connecting points within a casting so that an optimum cross sectional shape can be achieved.

2.1.7 Improved corrosion behaviour

According to the chemical composition (nearly without Copper) the alloy A357 is to be classified as an alloy with a better corrosion behaviour than the conventional wrought materials of the 2xxx- and 7xxx-series.

2.2 Cost Reduction Aspects

One of the most important advantages of casting design is cost reduction. However, the magnitude of cost differences will also depend on the company's own production facilities for conventional construction types. During the last few years, MBB has made considerable investments in order to cover the increase of production rates in the civil aircraft section. This means that the economics of casting production have to match those of ultra-modern conventional milling and sheet-metal forming production. In spite of this, certain structural areas, mainly those where assembly costs are considerable, have shown their full qualification for production as castings.

Among the most important cost reduction aspects we may quote the following:

2.2.1 Reduction of part numbers

Besides the reduction of assembly work which will be explained later on, another important advantage consists in the fact that the number of circulating individual parts will be greatly reduced. Moreover there will be a reduction in the storage of plate and sheet material which will have a positive influence on the so-called buy-to-fly ratio.

2.2.2 Reduced assembly work

The reduction achieved in assembly work is mainly caused by the elimination of costly rivet connections used in compact structural areas for the transmission of high loads. In most cases, the rivet connection is not easily accessible and requires, moreover, labour-intensive reaming of drill holes. In addition, it is often necessary to provide the mating surfaces of several milled parts with shims in order to obtain the required tolerances. This is a cost-intensive procedure since this type of fitting work can be performed only manually.

2.2.3 Less milling work

As already explained, the above-mentioned compact structural areas require, if they are realized in differential design, a build-up of highly complex milled parts with complicated geometry and fuselage or wing loftlines which can be obtained only by means of traverse milling procedures. Use of titanium castings - see Fig. 9 - will greatly reduce labor and cost-intensive titanium machining operations.

2.2.4 Less drawing expenditure

This criterion comes as a consequence of the reduction of part numbers and assembly work.

Of course these reductions will have an effect only in the non-recurring cost sector.

2.3 Weight Aspects

Another important design feature is the weight. For a designer of civil and especially military aircraft structures it is extremely important to comply with specified weight requirements.

This means that the specific possibilities of casting have to be rigorously used, taking into account the reduced stress level and the additional casting factor. As a matter of fact, a casting has a chance of being introduced only if its weight is identical with or iferior to the weight of conventional parts. Higher weights will rarely be accepted in military programs, even if the purchase price is lower.

In many cases it is possible to compensate the weight handicap by making the most of casting features such as:

- Run through of load path
- No overlapping
- Integration of edge reinforcement
- Uninterrupted web crossings
- Optimizing of cross sections with regard to stress requirements
- Integration of structural parts as much as castability
- Possibility of using smalles corner radii

In the case of some components, a combination of these facters and the specific size, geometry and function may lead even to a reduced weight.

Other efforts ultimately aimed at minimizing the weight are:

a) Hot-isostatic pressing (H.I.P.) of aluminium castings (already standard procedure in the case of titanium parts)

b) Introduction of higher strength aluminium alloys (A357 Cu, K01)

c) Chemical milling of aluminium castings.

These subjects are under consideration but have not yet been finalized.

The necessary tests will be time-consuming and costly. The first information available is certainly positive:

ad a): *The HIP procedure used for aluminium components will improve the scatter range of mechanical characteristics as well as fatigue behaviour.*

ad b): The undisputedly higher strength values are counteracted by an inferior castability. Aircraft structures comprise areas with extremely thin walls, i.e. minimum wall thickness will have to be reduced by the foundry in order to make 100 % use of the advantages of these alloys.

ad c): Chemical milling would be every useful for the design engineer in his effort to optimize weight. However the tests undertaken hitherto in this regard have left a lot of questions unanswered since the surfaces produced in the chemically milled areas are not yet satisfactory.

In should not be forgotten that this process would cause considerable costs for masking and unmasking operations on complex components. Additional costs will incur if the chemical milling process calls for a bath composition differing from that used for standard sheet material.

2.4 Manufactured castings

The following paragraps will contain a detailed description of the components which have been chosen by MBB-UT for casting design and manufacture. These are the components on which we have based our explanations, statements and practical experience with production items.

The first two items, Nib and Intake Floor, *Fig 5 and 6, have been widely* publicized so that they are well known. They were meant as test items only and although test results were excellent they were not practically used since production was already at an advanced stage.

As far as the Intake Floor are concerned *it should be added that this component* was dimensioned with a casting factor 1.0 as determined by stress calculations. The item was statically and dynamically tested.

The following table will give a survey on the results obtained:

Intake Floor	**COMPONENT TESTS**	
	static	dynamic
Casting design	Withstoad limit load 39.3 KN Rupture at 101.5 KN	47 200 cycles
Conventional design	Withstoad limit load 39.3 KN	24 020 cycles

Both designs complied with static requirements. As far as dynamic requirements are concerned, the casting was better by a factor of 2. However, no statement can be made with regard to dispersion since the number of tested components was limited. The reason for the better results furnished by the casting is to be found in the influence of geometry. A comparison of Woehler-curves of casting material and wrought alloy shows that the wrought alloy values are better.

In the conventional design, disadvantages are introduced by the unavoidable inhomogeneous structure caused by connecting elements (off-sets).

Same as with the Nib casting, casting-adapted design led to a good dynamic behaviour.

These items realized within the scope of the WST-M program inspired such confidence in the applicability of castings for aircraft structure that it was decided to launch series production of the following items:

Track I and II, Flap Fittings (Fig. 7 und 8)
These fittings represent the load introduction areas for the inner flap of A/C A320 which means that it is in this area that the lift forces are transmitted into the tracks of the landing flap guidance system. They are integrated into a CFRP structure by means of rivets. This requires an extreme geometrical accuracy of the loft surfaces especially since the stress office will not accept liquid shims of more than 0.5 mm thickness. The Track I component is manufactured as investment casting in accordance with the waste-wax process. The Track II component is designed as low-pressure sand casting.

Spoiler Fitting A310 (Fig. 9)
The spoiler of A/C A310 rest on three bearings. The central bearing is also used for the attachment of the actuator. In view of the reduced overall height and other space limitations, the component has to be manufactured in titanium in order to comply with static requirements. Since the casting is inserted into a CFRP pocket in order connect it to the surrounding CFRP structure, the demands made on accuracy are high, in spite of the use of shims.

MOB Tank Fitting (Fig. 10)
MOB stands for War Reserve Drop Tank. The fitting shown serves to take up the bomb rack on the wing of the TORNADO fighter aircraft. Although this is, strictly speaking, no structural aircraft item, it is certainly an interesting component because of its large quantity. At first, the casting had been designed as conventional aluminium sand casting. However, since this casting technique could not fulfill requirements such as tolerances positional accuray, etc. it was decided, during the production run, to switch over to the gravity die casting method. The new casting produced in accordance with the new procedure fulfils all requirements also with regard to economical aspects where even an improvement has been reached.

2.5 Sum up

Summing up the experience gained from the investigations carried out on these components we wish to print out that each component represents its own experience potential, depending on material and geometry. Generally the following can be said from the designers point of view:

2.5.1 After an initial phase with some problems there is now a normal use of the series parts in our production line.

2.5.2 It is easier for the foundry to achieve technological properties than dimensional accuracy.

2.5.3 The castings we have defined for use on aircraft structures seem to come up against the limits of casting feasibilities as far as their complexity and wall thicknesses are concerned.

2.5.4 From experience we can say that it is most helpful if, during the first discussions between designer engineer and foundry, the future mold tool manufacturer is already involved.

2.5.5 For this type of complex structural components, the introduction phase is much more difficult and time-consuming than for conventional castings. There will always be several repair cycles within the foundry.

2.5.6 In conclusion of this chapter on the advantages of casting design it should be impharised again that fulfilment of weight requirements is of utmost importance for the design engineer. Fig. 4 shows the cost and weight situation related to a number of different component geometries and sizes found in aircraft structures. From the comparisons made it becomes evident that the weight balance becomes negative with increasing component size whereas the cast advantage remains unchanged, at least under today's conditions.

This means that, in order to achieve wide application of casting technology in aircraft structures, every effort should be made to improve the weight situation for large-sized components. For this purpose, all weight-influencing parameters such as:

- casting factor
- strength properties of aluminium alloys
- tolerances
- minimum wall thickness

will have to be adequately improved.

3. Designer's Handicap

In addition to its widely advertised advantages, each type of design also has its share of drawbacks. They should not be forgotten when it comes to drawing comparisons with other manufacturing processes. There are negative factors which can be defined and calculated, such as:

- casting factor
- lower stress level

Then there are other facts which, although they cannot be expressed in figures, constitute quite a handicap for the designer who wants to develop and introduce a casting component. Some of these facts are:

- different quality level of foundries
- aversion to casting design in other departments
- short development phases in aircraft programs
- more steps between software and hardware
- communication with the foundry
- single source of castings

In the following paragraphs there different handicaps will be described from the designer's point of view. By this detailed description we hope to show problems and trouble spots with the objective of minimizing then with the help of all persons and services concerned with the development of a casting element.

3.1 The "Casting Factor"

The factor represent the biggest disadvantage since it greatly influences weight. For this reason, a designer of aircraft structures has always given castings very "bad markes" since he will always aim at one thing - to develop the lightest possible functional structure; In accordance with FAR 25, this factor is fixed at 1.25 to 2.0 for criterial parts.

In their connection we would like to point out that MIL A.8860 even gives a casting factor of 1.33, which we fail to understand. In the FAR range comprised between 1.25 and 2.0, the factor varies in accordance with component class and tests performed on the respective casting. This means a considerable weight penalty in comparison with other designs and processes.

3.2 Lower stress level

This fact belongs to the area of aluminium castings as there is no such probleme with cast titanium components. However, since aircraft structures consist mainly of aluminium, elements this constitutes a real drawback. As a matter of fact, the strength properties of casting alloy A357 and a standard plate material differ in the order of minus 30 %.

3.3 Different quality level of foundries

Inspections carried out on different components have shown that foundries do furnish different results with regard to metallurgical properties and obtainable tolerances. This is certainly due to the different procedures and individual process steps used.

3.4 Aversion to casting design in other departments

After having made up his mind on the casting possibilities of a certain component, the designer will be faced with the necessity of having to carry through his idea with other specialist departments which have a share of the responsibility for the component in question. It is mainly the stress office which, influenced by experience gathered a very long time ago, is still suspicious of the introduction of castings in aircraft structures. Teething troubles which, by the way, appear in every new manufacturing technology - in this connection we may quote the introduction of CFRP components - are eagerly taken up and then passed on in an exaggerated form.

In the company's own workshops - milling and sheet metal working and assembly - which would see their workload reduced by the introduction of casting techniques, the designer will not meet with enthuastic support either. They will reproach him for endangering jobs.

3.5 Short development phases in aircraft programs

In military and civil aircraft programs, the period comprised between go-ahead and first flight is getting shorter and shorter which means, among other things, that the design engineer has hardly any time left for the development of alternatives. However, it is only by comparing several variants that he has the possibility of finding the optimum solution with regard to cost and weight.

If the components is to be a casting then additional time will be required to find a suitable foundry within the already very short development phase. Moreover, an optimum casting can be realized only in close contact with the foundry entrusted with manufacture which means that a casting require a second development phase. As will be explained later on, the definition of a casting requires more steps than a conventional design - and in this short development phase at that. - Moreover it takes approximately nine mounth to manufacture the casting tools.

3.6 More steps between software and hardware

A description of the manufacturing process of a casting component and of a conventional item which can be produced on one's own premises, will clearly show that the manufacture of the casting variant will require on increased number of work steps. This includes even some factors which constitute elements of uncertaintly for the design engineer. In most cases, he does not know at the beginning of his design work:

- the applicable casting method

- the foundry which will manufacture the item

- whether casting manufacture will fit into the time schedule

- whether potential foundries will have the necessary manufacturing capacity

- the tolerances which can be kept since this will depend on the method applied

A comparison of the two design processes shows clearly that, for the definition of a casting from software to hardware, the design engineer has a definitly bigger task before him.

The following table contains the different design process steps which directly affect the design engineer and his contribution:

Casting Design	Conventional Design
1. Pre-Design	1. Pre-Design
2. Discussion with foundries	2. Discussion with production plant specialists
3. Workshop drawing and test program	3. Workshop drawing, release and test program
4. Selection of foundry	4. Production support for start of series production
5. Final discussion with foundry	
6. Finishing and release of casting drawing	
7. Preparation and release of drawing for re-machining	
8. Cooperation for acceptance test and release for series production	
9. Production support for start of series production	

3.7 Communication with the foundry

During the design phase, the design engineer requires detailed information on casting technology. Questions will arise which can be answered only by a casting specialist. Long distances and requirements such as knowledge of another foreign language represent considerable handicaps.

3.8 Single source of castings

In view of the workloads, installations for the production of items manufactured in accordance with conventional differential designs are, in most cases, several times redundant. It is obvious that this cannot be done for castings since tooling costs would be definitely too high for a double or triple redundancy. This means, however, that production is immediately put at risk in case of damage to the production equipment of the contracting foundry.

4. Conclusion and Prospects

MBB-UT has introduced castings into the primary aircraft structure and will continue to do so on the basis of the cost reduction potential and the experience gathered. It has been demonstrated that castings, same as other solid parts, can also be integrated into a CFRP structure.

From the designers' viewpoint we would like to emphasize again that dimensional accuracy is of utmost importance so that castings can be introduced without problems into the adjacent structures.

In conclusion it can be said that the components most suited to casting design are mainly parts with a box-type geometry where normally several milled parts would have to be riveted together or where steel or titanium welded parts would have to be called for. Other potential castings are grid-like structures which, in conventional manufacturing procedures, require a lot of assembly work.
However, main condition for this wider application of castings in aircraft structures seems to be the reduction of the handicaps listed in Chapter 3.

From the designers' viewpoint, this would require the following measures and activities:

Designers' handicap	What to do	Effect on	Action by
Casting factor	Elimination or reduction	Weight	Airworthiness authorities
Lower stress level	Improvement of aluminium alloys and casting techniques	Weight	Foundries
Aversion to casting design	Wide spread of casting information	Acceptance of casting as standard production process	Users (aircraft manufacturers)
Different quality level of the foundries	Information about the different processes for the designer	Wide application of casting design	User
Short development phases	Adequate scheduling to permit comparison of alternative	Realization of cost-effective design	User/Foundry
More steps for casting design between software and hardware	Information about these steps for the designer	Diminishing of designers' aversion to casting design	User
Communication with the foundry	Designation of a contact person for foundry and user. Regular meetings between both parties proposed	Reduction of development time and avoidance of mistakes and misunderstandings	User and foundries
Single source of casting	Proposal: Direct cooperation between two foundries for the manufacture of one item.	Production guarantee	Foundries

The purpose of this expose is to promote the application of casting technology in the manufacture of aircraft structures. For the designer it is of utmost importance to find out in time which component permits cost-effective casting design in comparison with another equally functional type of manufacture.

Another point which would largely contribute to a wider application of casting technology is the minimization of the casting factor. This factor was introduced quite a while ago in order to cover a number of uncertainties with regard to strength properties and metallurgical tests. In these areas, technology has made a great leap ahead in the course of the last few years. Todays' castings designed for application in aircraft structures are subject to definite quality requirements and have to be manufactured in accordance with definite technical specifications and data sheets for delivery. This means, for example, that the minimum values concerning the strength properties of the casting are clearly defined. Static dimensioning of the casting is carried out on the basis of these values and all dispersions have to be well within these limits.

We, the designers, hope for a wider application of casting technology (see Fig. 11) because of the liberty of design and the cost potential offered. We will help to remove the slumbling blocks and handicaps still in our way.

References:

(1) WST-M-Program (Wirtschaftliche Struktur-Technologien-Metall)
1th - 8th Review, MBB-UT, Bremen

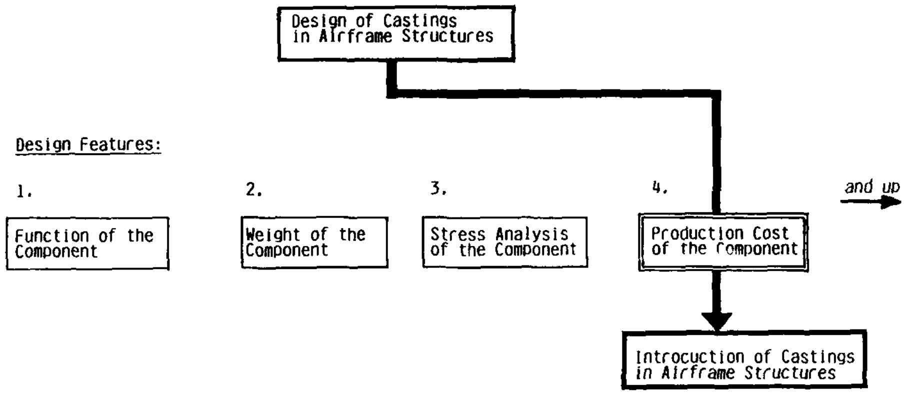


Figure 1: Introduction of Castings from the Designers' View

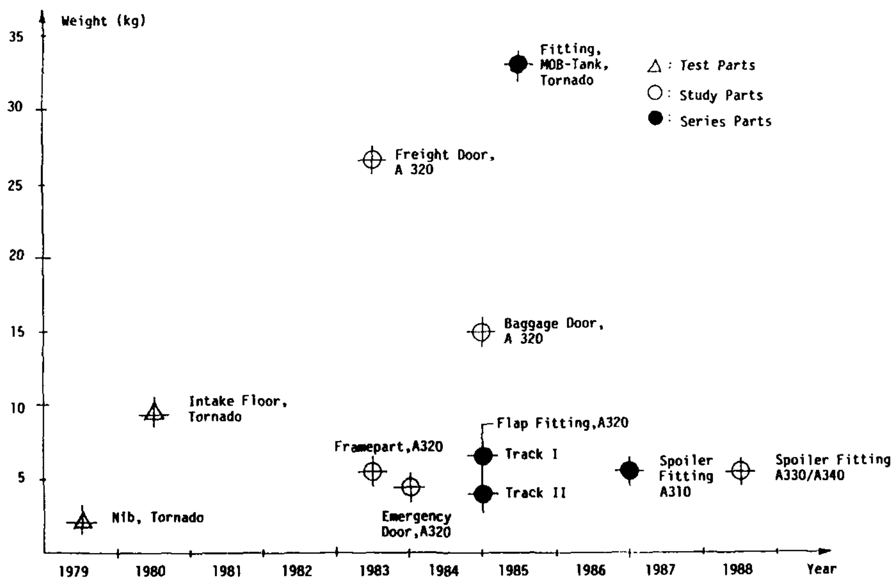


Figure 2: Castings for Airframe Structures by MBB

Advantages of Casting Design

- **Design Aspects**
  - Realization of complex structures as one piece.
  - Run through of load path
  - More design exemptions
  - Better fatique design possible
  - Less rivet holes
  - Better corrosion behaviour
- **Cost Reduction Aspects**
  - Reduction of part number
  - Minimization of assembly work and avoidance of complex riveting
  - Less milling work of complex shapes
  - Less drawing expenditure

Figure 3: Advantages of Casting Design

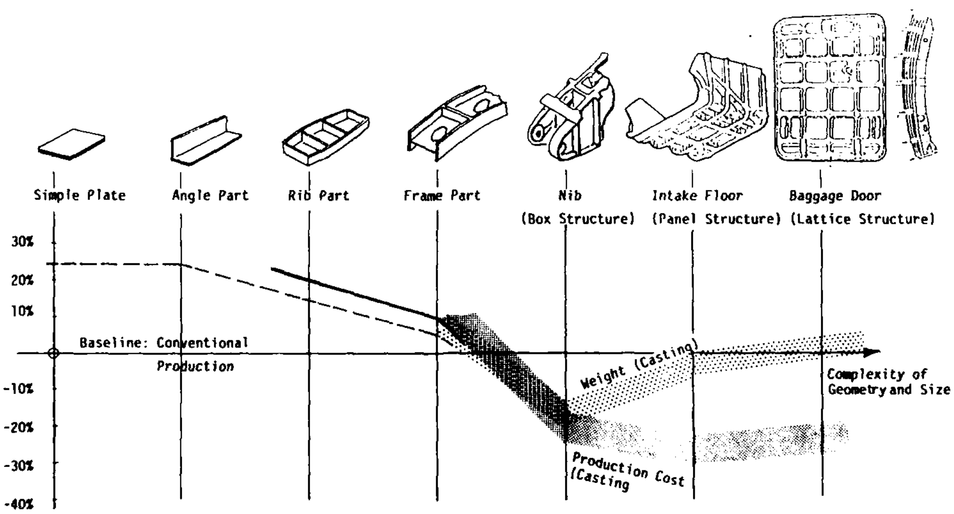


Figure 4: Weight and Cost accord. to the Castings' Geometry

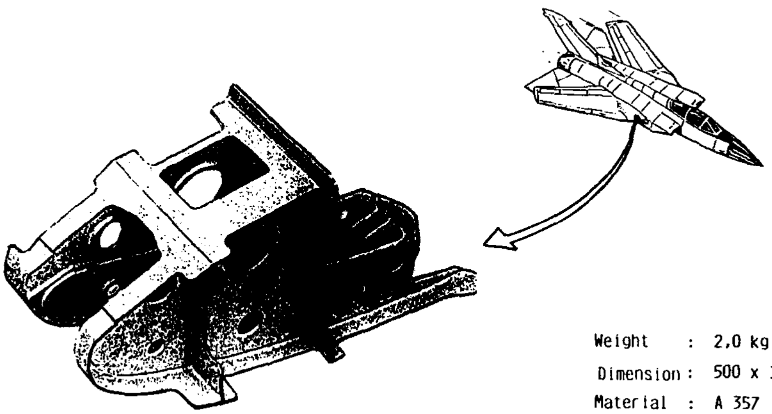


Figure 5: Nib, Tornado (Test Part only)

Weight : 2,0 kg
Dimension : 500 x 190 x 300 mm
Material : A 357
Process : Investment Casting
Funktion : Bearing structure for Krueger flap and actuator.

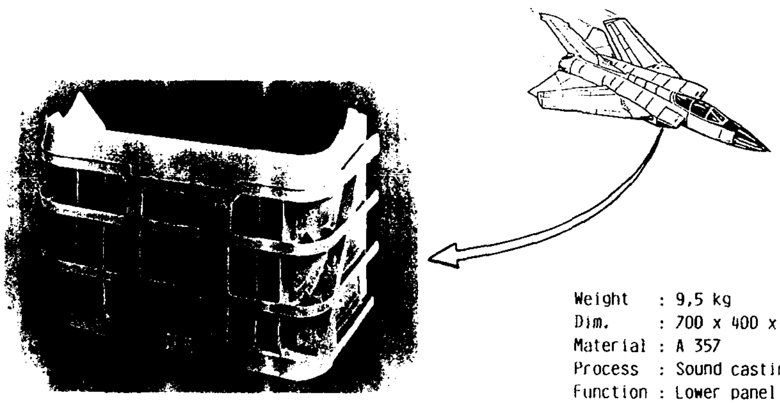


Figure 6: Intake Floor, Tornado (Test Part only)

Weight : 9,5 kg
Dim. : 700 x 400 x 500 mm
Material : A 357
Process : Sound casting
Function : Lower panel of forward intake structure

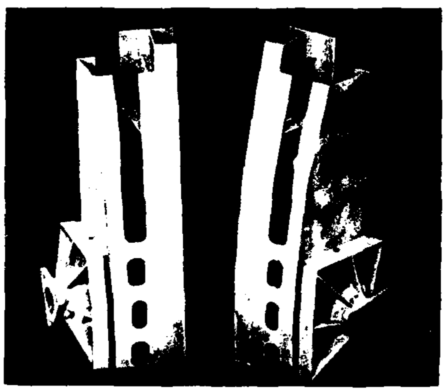
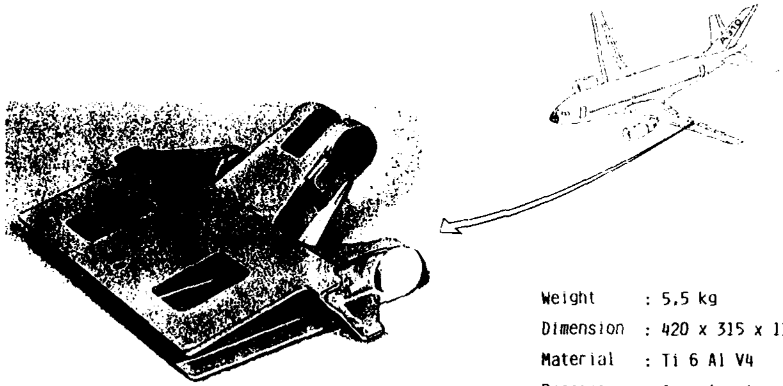


Figure 7: Flap Fitting "Track 1" (Series Part)

Weight : 6,5 kg
Dim. : 557 x 255 x 190
Material : A 357
Process : Investment casting
Function : One of two track bearings fitting of the Inner Flap, A 320.

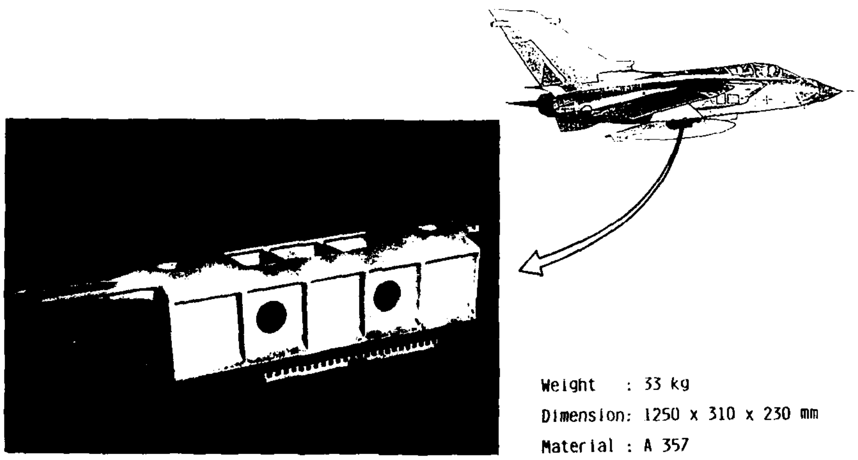
Weight : 3,3 kg
Dimension : 520 x 255 x 115
Material : A 357
Process : Low pressure sand casting
Function : One of two track bearing fitting of the inner flap, A 320.

Figure 8 : Flap Fitting "Track II" (Series Part)



Weight : 5,5 kg
Dimension : 420 x 315 x 135 mm
Material : Ti 6 Al V4
Process : Investment casting
Function : Centre bearing and actuator fitting of the spoiler

Figure 9 : Spoiler Fitting (Series Part)



Weight : 33 kg
Dimension: 1250 x 310 x 230 mm
Material : A 357
Process : Gravity die-casting
Function : Suspension fitting for pick up (bomb lock)

Figure 10 : MOB-Tank Fitting, War Reserve Drop Tank (Series Part)

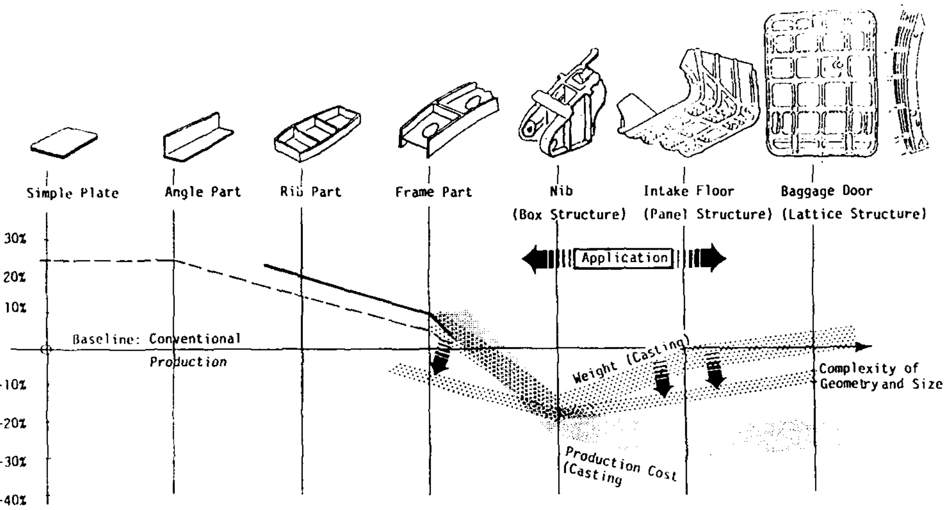


Figure 11 : Wider Application of Casting by Improvement of the Weight Situation

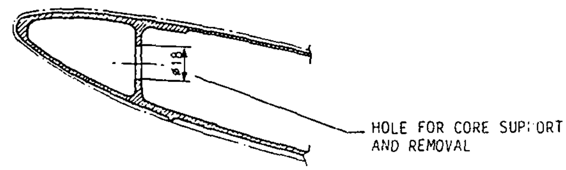


Figure 12: Lip of the "Forward Inlet" casting

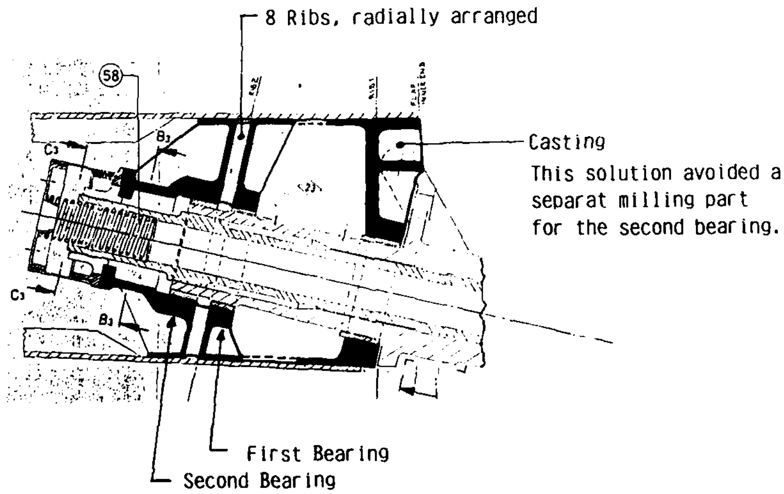


Figure 13: Track I - Fitting, Fail-Safe-Solution

EVALUATION OF TITANIUM CASTINGS FOR AEROSPACE COMPONENTS

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1. ABSTRACT

A significant potential cost saving could be obtained by the introduction of titanium casting in lieu of parts machined from plate or conventional forging.
In order to verify the production quality together with the behaviour of the cast material and scatter of the results, a complete program of static, fatigue and cut-up tests has been performed.
The investigations were carried out on three different structural components in order to obtain a complete characterization of the cast material by dissection specimens and structural tests on full scale components.
Parts were obtained using two different casting processes, rammed graphite and lost wax.
This paper presents the results obtained on the titanium cast parts in comparison to the machined ones.

2. INTRODUCTION

The aerospace technology development is oriented, mostly, to achieve the following goals:

- Increase of performance.
- Decrease of production costs.
- Decrease of service costs (Inspections, repair, maintenance, etc.).
- Increase of safety and reliability.

Having these goals in prospect, the choice of materials has great importance because the aircraft performances are directly in relation to the behaviour of materials used to manufacture the structures; nevertheless it is important, from technical and economical point of view, the type of semifinished product from which the parts are obtained.

Since several years, in fact, the "Design to cost" philosophy takes place to push the designer to obtain parts at low production costs with unchanged technical requirements for the aircraft performance.

From this point of view it can be interesting, and also applied with benefit, the use of castings that can allow the manufacturing of complicated structures without welding and/or riveting resulting in lower production costs.

For the above mentioned reasons, AERITALIA performed some investigations on structural cast parts presented and divided in two major programs.

3. FIRST PROGRAM TESTS

The research was conducted in the mid '70's only on Ti 6Al 4V, first of all on a typical part reproducing a flap track section as shown in fig.1 and in a second step on the full scale flap track as shown in fig. 2.
All the components were obtained using Rammed graphite mould casting process.
The investigation was divided in three principal activities:

- Nondestructive evaluations
- Test on dissection specimens
- Static and fatigue tests on structural components

3.1 Nondestructive evaluations

Following activities were performed:

- Visual inspection

- Dimensional control (Tolerances, surface roughness)
- Hardness
- Penetrant inspection
- Micro analysis
- Chemical analysis
- X Ray

3.2 Test on dissection specimens

Several tests have been performed, not only to control and qualify the products but also to Know the behaviour, in general, of the titanium casting to evaluate the possible utilization on the aircraft structures.
For this reason the following tests have been performed:

- Tensile test
- Shear test
- Fatigue tests
- Fracture Toughness test

Type of specimens are shown in figg.3 and 4.

3.3 Static and fatigue tests on structural components

In order to compare the static and fatigue behaviour of the structural titanium casting components with the same ones obtained by machining from solid plate, a complete program of static and fatigue tests has been carried out.

4. RESULTS OF FIRST TEST PROGRAM

4.1 Nondestructive evaluations results

- The quality, in general, was judged excellent and also the results of X Ray and penetrant inspection indicated that satisfactory casting was achieved with good conformance to the requirements.

- Chemical analysis is reported in Table I, which indicates the obtained values are in agreement with the specification requirements.

- Dimensional controls, as shown in tables II and III revealed remarkable deviations from the drawing requirements.

- It was also noted, that the dimensional errors did not always occur in the same area of the checked cast parts, but generally in different areas. This means that a constant producibility of the parts was not yet achieved.
  In addition, all the parts, especially the full scale flap track components, showed great distortion and also in this case not always with the same shape.

- Micro examinations of some sections, taken from different positions of the casting, indicates that the grain structure is regular. (See photos in fig.5).

- Hardness values obtained from different castings are shown in table IV.
  The values are in agreement with the specification requirements.

4.2 Dissection specimens test results

Tests were performed in order to evaluate the static strength, the fatigue characteristics and fracture mechanics properties of some samples of Ti 6AL 4V alloy castings in the annealed condition.
The test specimens were obtained from nine cast sections simulating a probable flap track geometry for a possible application in the production aircraft.

- The test specimens were cut according to the scheme shown in fig.6.

- Tensile tests results are shown in table IV.
  A large scatter in results has been noted, specially as far as the yield tension strength values are concerned and also the mean value is lower than the minimum required.

- Shear tests results are shown in table V.

- The results of fatigue test on notched (Kt = 3.1) and unnotched specimens at constant amplitude (R=O) are presented in figg. 7 and 8.
  The fatigue life for notched specimens is lower if compared with the corresponding data for the wrought products in the same alloy Ti 6AL 4V.

- Fracture toughness resistance was checked using center crack specimens, results are presented in table V.

4.3 Static and fatigue tests results

A total of twenty-four specimens from different heats, representing the flap track were produced in order to be statically and dynamically tested.
Thirteen specimens were statically tested up to failure whilst ten specimens were dynamically tested up to failure.
One specimen was not tested because was out of tolerance.

4.3.1 Static test

The specimens were fitted to a strong dummy bracket by their two support lugs (see photo in fig. 9).
The connection to the rig was not completely representative of the actual one between the flap track and its supporting bracket but strong enough to assure the failure of the specimens in order to evaluate the scatter of results. All results of the static tests are summarized in table VI.

4.3.2 Fatigue test

The flap track specimens were fitted to a steel dummy bracket incorporating the two bolts connection to the relevant rib, not taking into account the connection between the tracks and the shrouds.
In order to guarantee an accurate load application, the moveable and fixed loads have been applied on both sides of each track by means of two parallelogram elements (see photo in fig. 10).
All the specimens were tested with a load spectrum reproducing 16.000 U.F.H. (see diagrams in fig.11) composed by two sequences called A and B repeated as follows:

Sequence A	400 times
Sequence B	4 times

The applied loads were continously recorded and compared, through the computerized system, with the required time history.
Periodic inspections of the test structure were made throughout the test in order to detect possible crack start or other damages.
All results of the fatigue tests are shown in table VII.

- Examinations by scanning electron microscope of the failure areas after the residual strength tests evidenced the presence of large crack propagations occured during the fatigue tests and not detected by the visual inspections performed.
  Some photos are shown in fig. 12.

5. SECOND PROGRAM TESTS

After the first experience on flap track specimens not completely satisfactory for the low yield strength, low fatigue behaviour and above all for the remarkable deviations in dimension tolerances, AERITALIA has performed in 1986 a second test program on other structural components to be utilized in production aircraft.
The decision has been taken also because the state of the art for titanium casting had increased substantially over the last several years in the areas of dimensional control and structural integrity specially for investment casting (lost wax).

- In this second program two different flight control quadrants, (see photos in fig. 13), have been qualified by dissection specimens.

5.1 Non destructive evaluations

The same activities as per the first program have been performed.

5.2 Tests on dissection specimens

Only tensile tests have been performed due to the fact that the components are not critical in fatigue.

6. RESULTS OF SECOND TEST PROGRAM

6.1 Nondestructive evaluations results

Also in this case the quality, by visual inspection was judged excellent and the results of X Ray and die penetrant indicated that satisfactory investment casting was obtained.
Also for these components the Ti 6AL 4V was used and in order to eliminate all potential porosity the parts were hot isostatically pressed (HIP) at 900 °C (1650 °F) for 2 hours and 100 MPa (14,5 KSI) in argon.

- Dimensional controls revealed no significant deviations from the drawing requirements.

- Chemical analysis, reported in table VIII indicates the values are in agreement with the specification.

- Micro examinations indicate that the grain structure is regular (see photos in fig. 14).

- Hardness values, according to the specification requirement, are shown in table IX.

6.2 Dissection specimens test results

A total of twelve specimens (six per each components) were tested.
Tensile test results are shown in table IX.

- This experience was considered satisfactory and AERITALIA decided to utilize the ast parts on the production aircraft.
  Unitil now, the dimensional controls performed on production parts revealed no significant deviations from the drawing shape.

- Mechanical characteristics results revealed good tensile properties generally from 9% to 15% better than the specification requirements with a low scatter in comparison to the results obtained in the first test program.

7. CONCLUSION

- These experiences, especially the second one, confirmed the progress made over the last ten years in the production of castings particularly in the areas of dimensional conformance and structural integrity, evidenced by the components today in production;

- Also, mechanical tests performed revealed a substantial increase of the characteristics with a satisfactory reproducibility and reliability.

- The market potential for the utilization of titanium castings as substitutes for forgings and machined parts is significant and several value analysis revealed that the application of castings reduce costs in the following cases:

  - Large number of parts, joined together to form one assy

  - Complicated parts with high complexity of machining (e.g. the parts qualified in the second test program).

- The traditional weight penalty due to the lower mechanical characteristic values and also to the utilization of the casting factor, can be, in the future, reduced because on one side we assist to the increase of the mechanical characteristics and on the other side to the reduction of scatter, which may lead in the near future to the adoption of smaller casting factors.

		VALUES OBTAINED FROM TWELVE CASTINGS (%)						
		C	O_2	H_2	N_2	Fe	AL	V
ACTUAL VALUES	min.	0.013	0.02	0.0051	0.015	0.17	5.8	3.8
	max.	0.023	0.18	0.0082	0.018	0.23	6.7	3.9
REF. VALUES	min.	—	—	—	—	—	5.5	3.5
	max.	0.08	0.20	0.015	0.05	0.30	6.75	4.5

TABLE I: CHEMICAL ANALYSIS

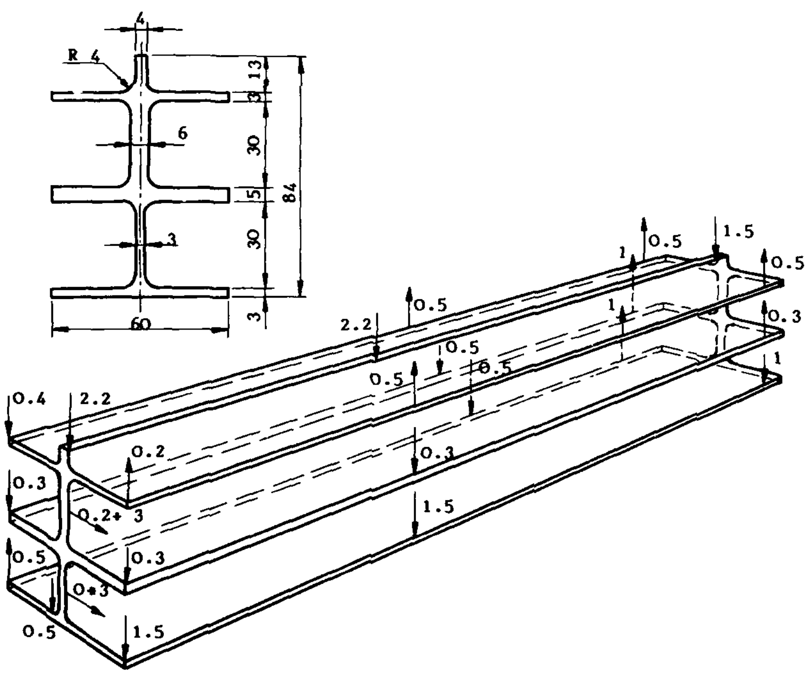
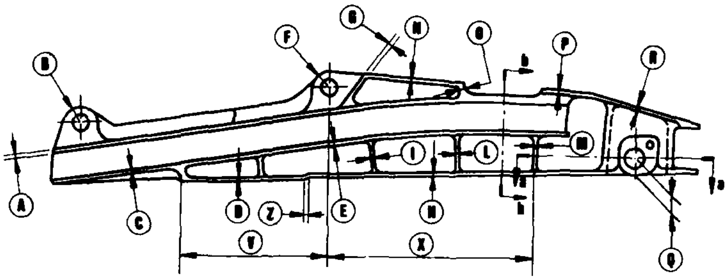
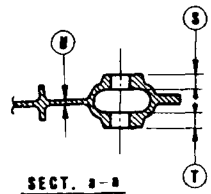


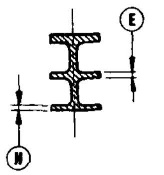
TABLE II: DIMENSIONAL DEVIATIONS FROM DRAWING SHAPE



CODE	REQUIRED VALUES (mm)	ACTUAL VALUES (mm)
X	209	208.1 + 209.8
Z	1	1.0 + 4.5
V	128	128.3 + 129
U	3	3.1 + 3.7
T	13.5	12.5 + 13.9
S	13.5	13.9 + 15.1
R	3	3.5 + 5.0
Q	17	16.5 + 18.0
P	3	2.7 + 4.0
O	3	4.0 + 6.5
N	3	3.0 + 5.2
M	2.5	3.2 + 4.5
L	2.5	3.3 + 4.3
I	2.5	3.3 + 4.0
H	3	3.0 + 4.5
G	2.5	1.7 + 3.0
F	15	14.9 + 15.2
E	5	3.7 + 7.0
D	3	2.2 + 3.7
C	4	3.8 + 5.3
B	15	14.8 + 15.3
A	3	2.0 + 3.2



SECT. a-a



SECT. b-b

TABLE III: DIMENSIONAL DEVIATIONS FROM DRAWING SHAPE

TEST NUMBER	GRAIN DIRECTION	Ftu (MPa)	Fty (MPa)	A (%)	HARDNESS (HRC)
1	L LT ST	824 968.3 941.7	745.5 696.5 569	7.15 7.15 7.15	32
2	L LT ST	892.7 892.7 883	794.6 677 529.7	6.8 10.7 10.7	31
3	L LT ST	873 873 912.3	716 677 500	7.15 7.15 7.15	33
4	L LT ST	932 883 892.7	843.6 745.5 804.4	6.8 6.25 6.25	35
5	L LT ST	968.3 863.3 902.5	814 775 833.9	8.9 6.25 3.14	30
6	L LT ST	941.7 968.3 968.3	784.8 657.3 784.8	8.9 11.3 12.5	31
7	L LT ST	951.6 968.3 941.7	706.3 706.3 784.8	7.15 6.25 6.25	36
8	L LT ST	912.3 968.3 941.7	745.5 647.5 775	8.9 6.25 9.35	33
9	L LT ST	932 922 883	824 814 804.4	8.9 6.25 6.25	--
MEAN VALUE	L LT ST	914.7 923 918.5	774.9 710.6 709.5	7.85 7.5 7.63	--
SPECIFIC. VALUE	--	931	829	7	39 MAX

TABLE IV: TENSILE AND HARDNESS RESULTS

TEST NUMBER	SHEAR STRENGTH (MPa)	Kc VALUES (MPa $\sqrt{m}$)
1	605.7	204.6
2	635.2	166.8
3	654.8	170.5
4	--	186
5	--	175.8
6	--	197.2
7	--	180.4
8	--	183.5
MEAN VALUES	632	183.1

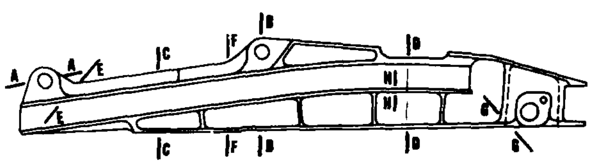
TABLE V: SHEAR AND FRACTURE TOUGHNESS RESULTS

TEST NUMBER	FAILURE LOAD (N)	FAILURE AREA
1	78410	SECTION A - A
2	80410	SECTION A - A
3	81490	SECTION F - F
4	83010	SECTION A - A
5	76750	SECTION A - A
6	77230	SECTION B - B
7	79380	SECTION A - A
8	84590	SECTION C - C
9	82440	SECTION A - A
10	81340	SECTION A - A
11	83430	SECTION A - A
12	86280	SECTION A - A
13	84820	SECTION A - A
MEAN VALUE	81506	
MACHINED TRACK	97310	SECTION A - A

TABLE VI: STATIC TEST RESULTS

TEST NUMBER	U.F.H.	RESIDUAL STRENGTH (N)	FAILURE AREA
1	6920	---	SECTION E - E
2	22880	---	SECTION G - G
3	10520	53150	SECTION H - H/A - A
4	10720	52810	SECTION H - H/F - F
5	5[illegible]30	---	SECTION D - D
6	6690	---	SECTION D - D
7	11480	---	SECTION D - D
8	4520	---	SECTION A - A
9	13720	---	SECTION B - B
10	16000	85660	SECTION D - D
MEAN VALUE	9702	---	
MACHINED TRACK	21500	77600	SECTION H - H/A - A

TABLE VII: FATIGUE TEST RESULTS



FAILURE AREA SCHEME

	VALUES OBTAINED FROM TWO DIFFERENT CAST COMPONENTS (%)						
	C	Fe	Al	V	O_2	H_2	N_2
ACTUAL VALUES	0.025	0.19	6.4	4.4	0.19	0.0016	0.014
SPECIFICATION VALUES	0.08	0.30	5.5 6.75	3.5 4.5	0.20	0.015	0.05

TABLE VIII: CHEMICAL ANALYSIS

	Ftu (MPa)	Fty (MPa)	A (%)	C (%)	HARDNESS (HRC)
COMPONENT "A"	955.2	875.7	10	15.5	--
	928.7	856.6	7.5	15.5	--
	958.5	875.7	10	16.0	--
	966.9	881.4	11.3	14.7	33
	974.5	899.3	8.9	13.2	32
	906.2	833.1	9.3	20.4	32
COMPONENT "B"	975.8	862.0	10	16	--
	975.8	888.8	10	15.5	--
	959.7	888.7	12.5	15.5	--
	899.4	823.4	10.7	15.6	31
	948.3	860.7	9.8	17.6	32
	937.9	871.0	9.3	17.6	30
SPECIFICATION VALUES	827.6	758.6	6	16	39 MAX

TABLE IX: TENSILE AND HARDNESS RESULTS

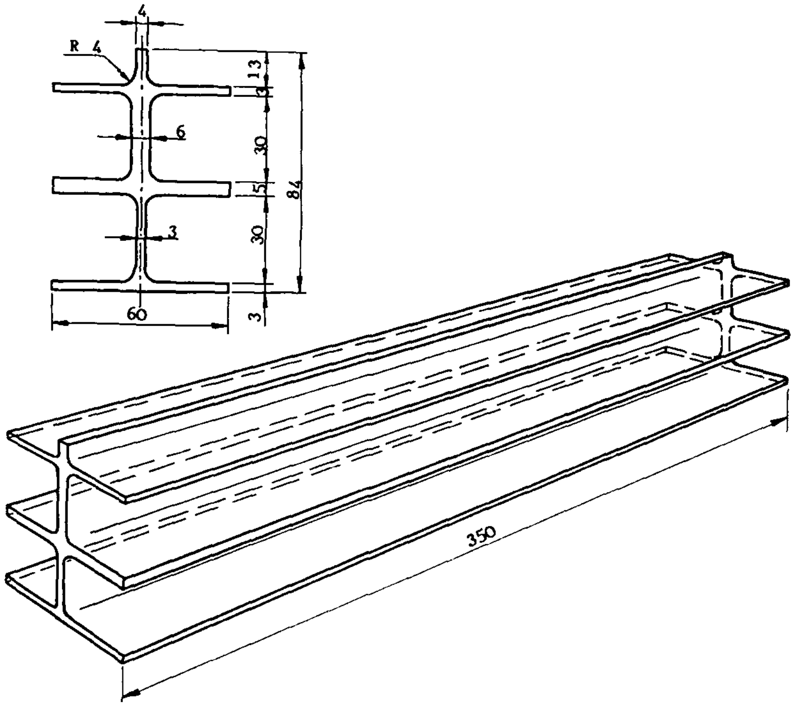


FIG. 1: TYPICAL FLAP TRACK SECTION

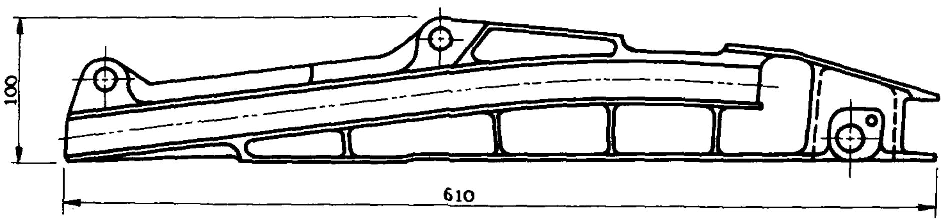
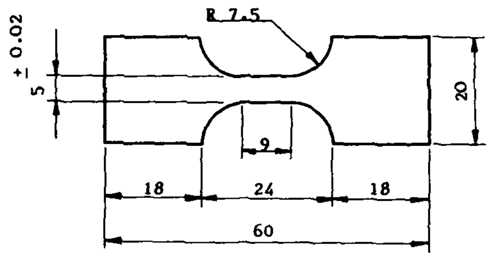
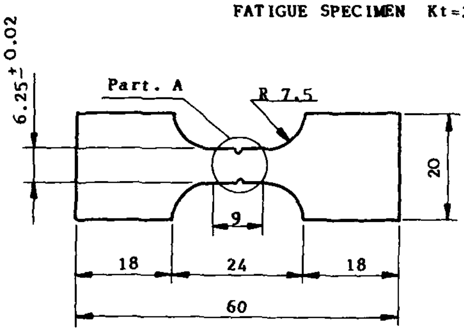


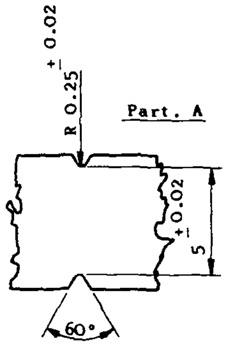
FIG. 2: FLAP TRACK

FATIGUE SPECIMEN Kt=1



FATIGUE SPECIMEN Kt=3.1





FRACTURE TOUGHNESS SPECIMEN

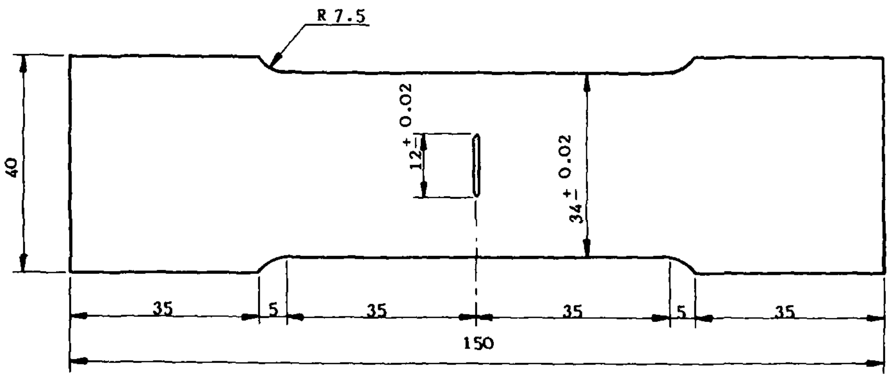
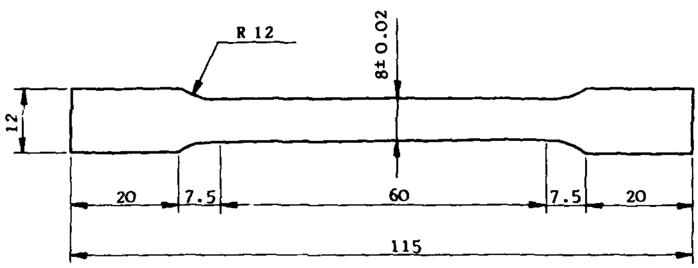
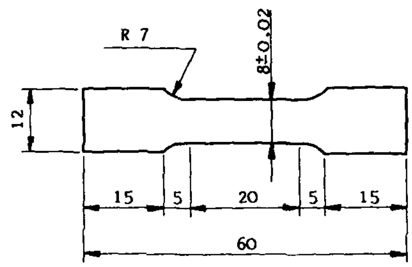


FIG. 3: TYPE OF SPECIMENS

LONGITUDINAL TENSILE SPECIMEN (THICKNESS 3 mm)



TRANSVERSE TENSILE SPECIMEN (THICKNESS 3 mm)



DOUBLE SHEAR SPECIMEN

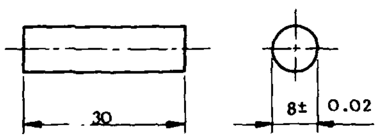


FIG. 4: TYPE OF SPECIMENS

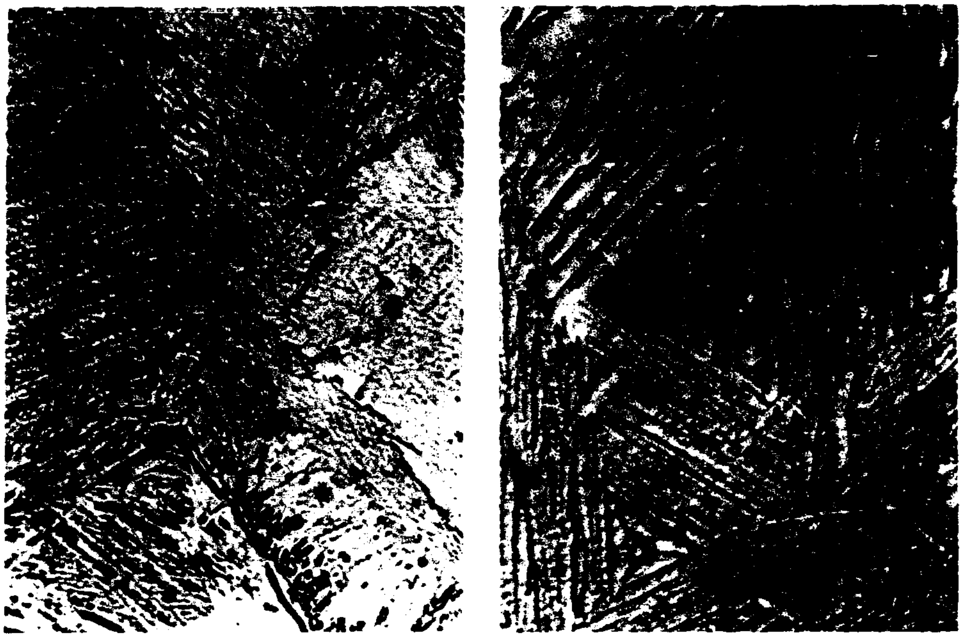


FIG. 5: MICRO EXAMINATIONS

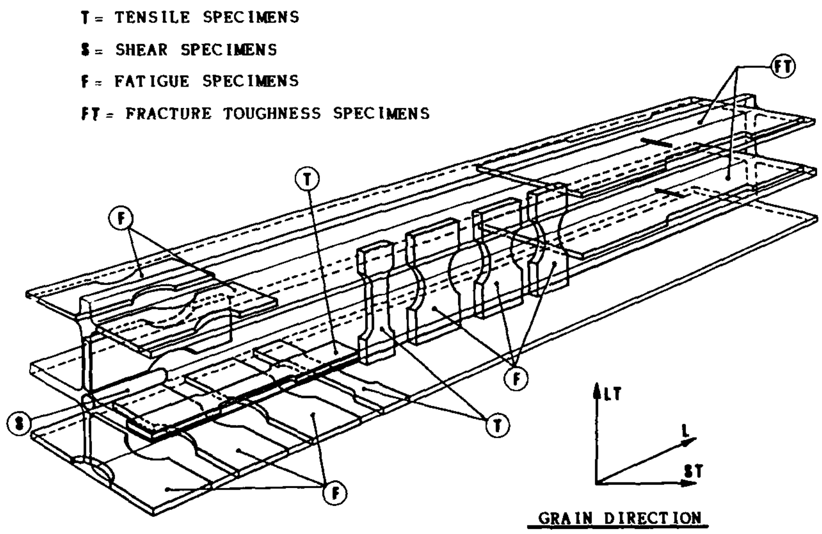


FIG. 6: DISSECTION SPECIMENS POSITION

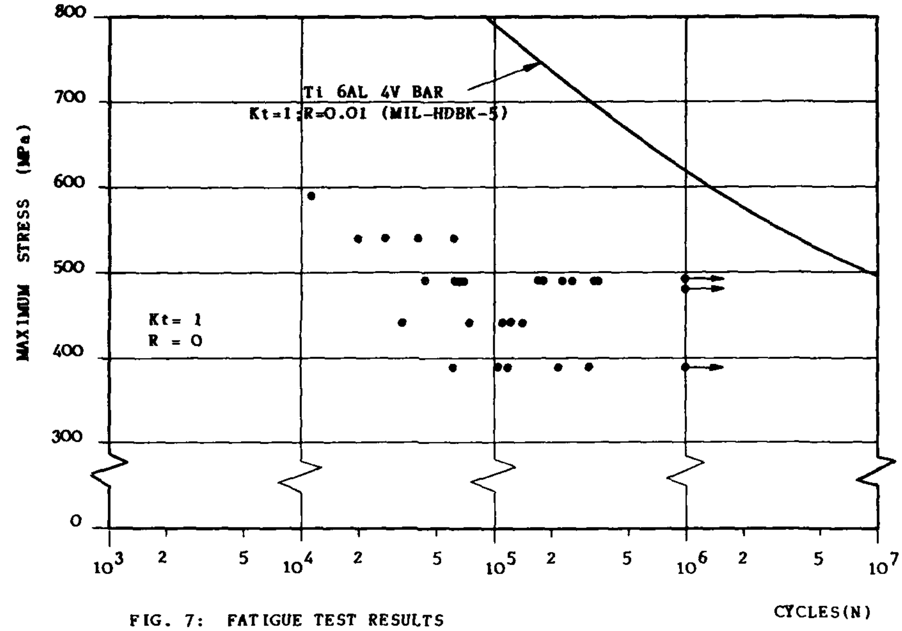


FIG. 7: FATIGUE TEST RESULTS

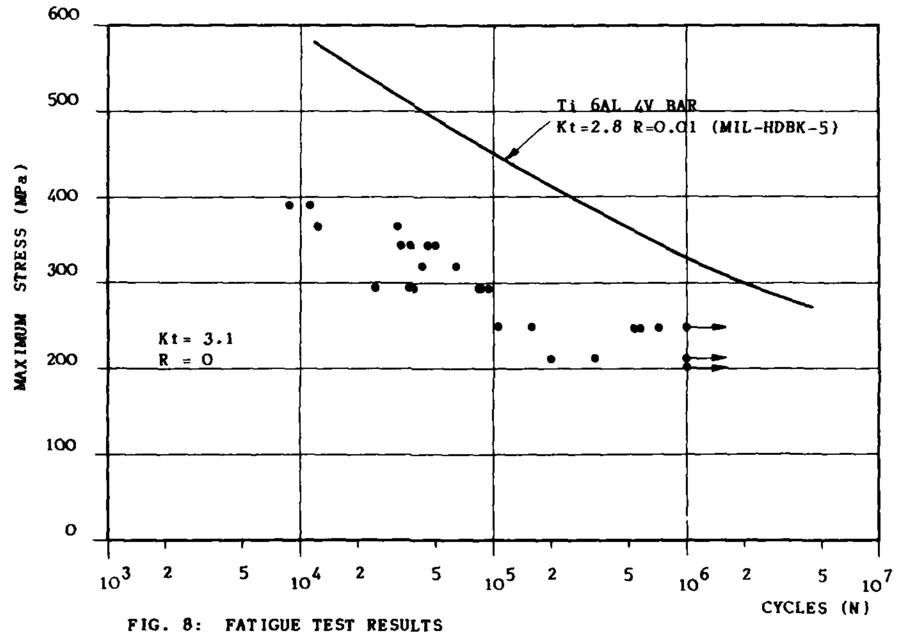


FIG. 8: FATIGUE TEST RESULTS

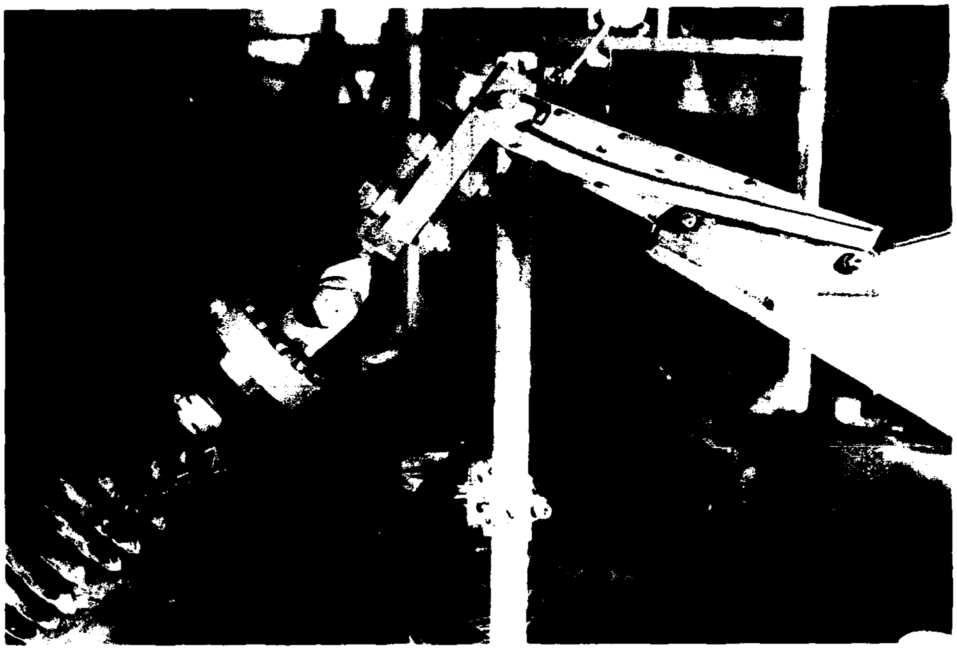


FIG. 9: STATIC TEST RIG

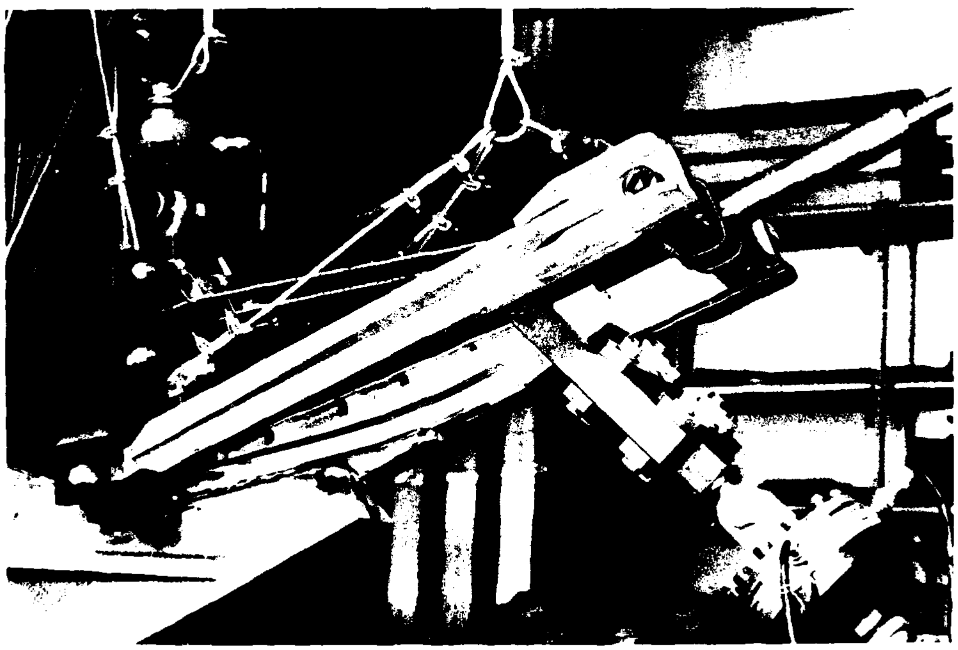


FIG. 10: FATIGUE TEST RIG

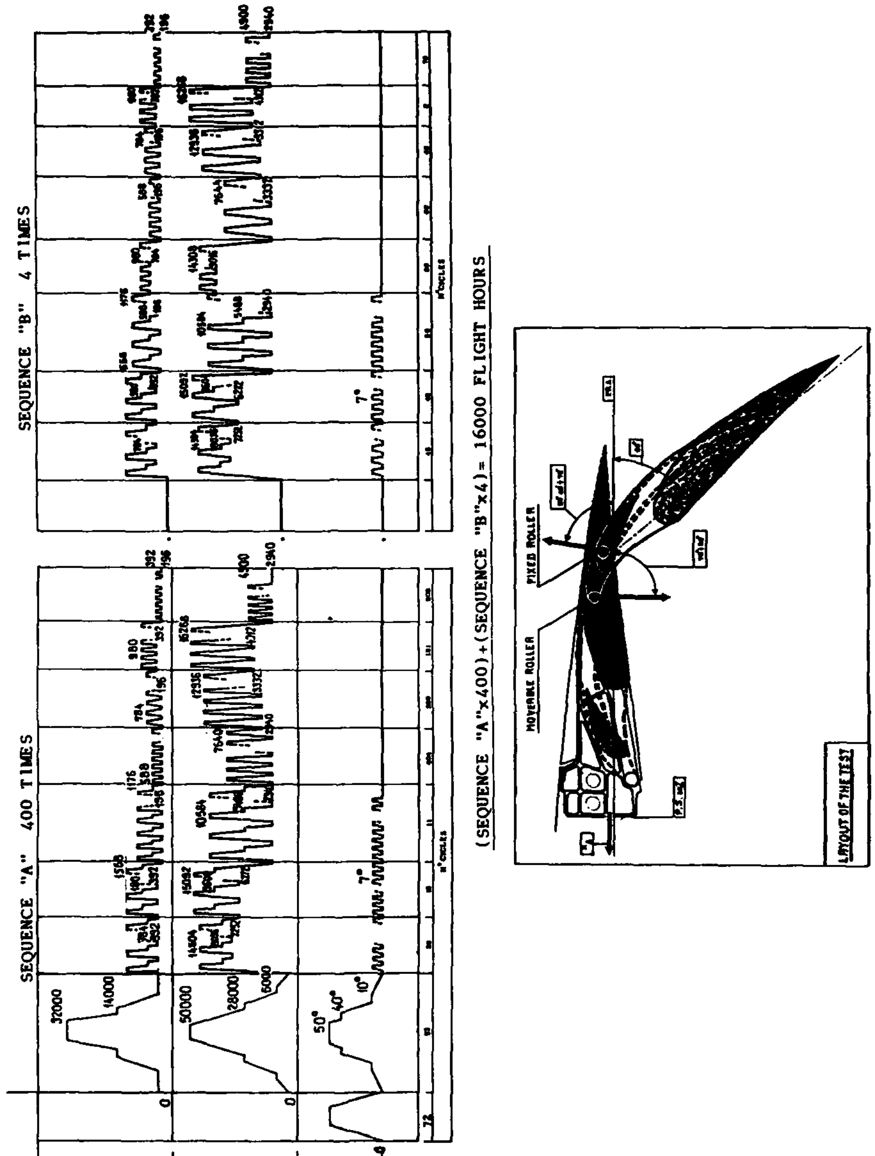


FIG. 11: TYPICAL LOAD SPECTRUM

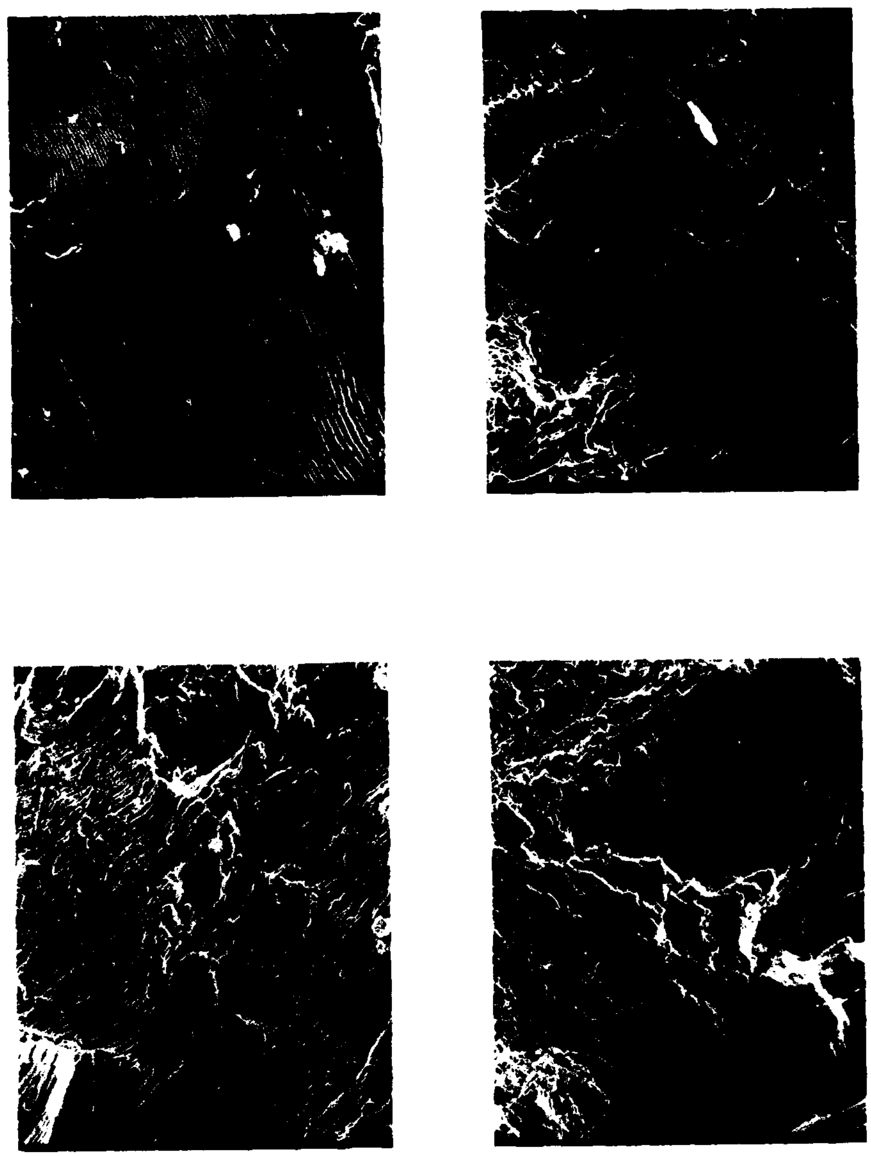


FIG. 12: SCANNING ELECTRON MICROSCOPE EXAMINATIONS

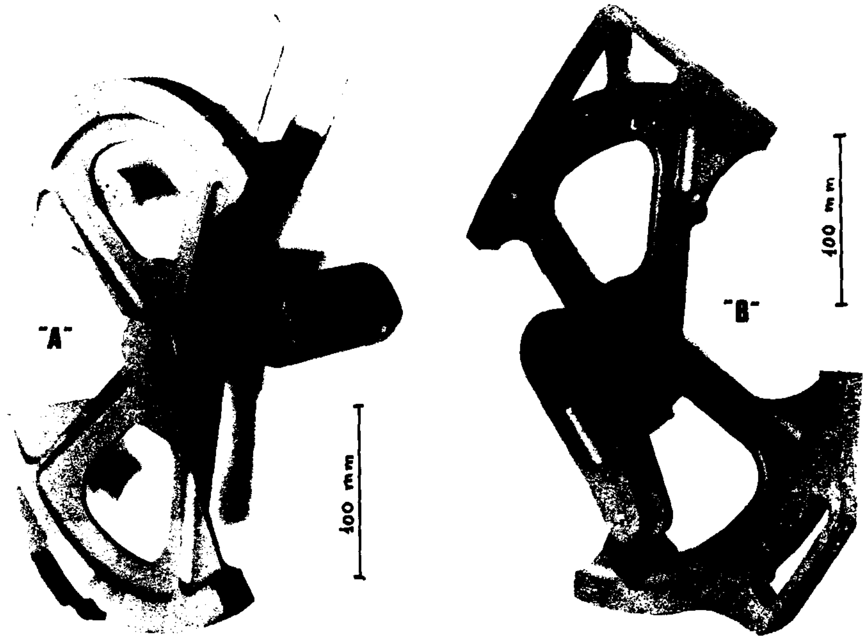


FIG. 13: FLIGHT CONTROL QUADRANTS

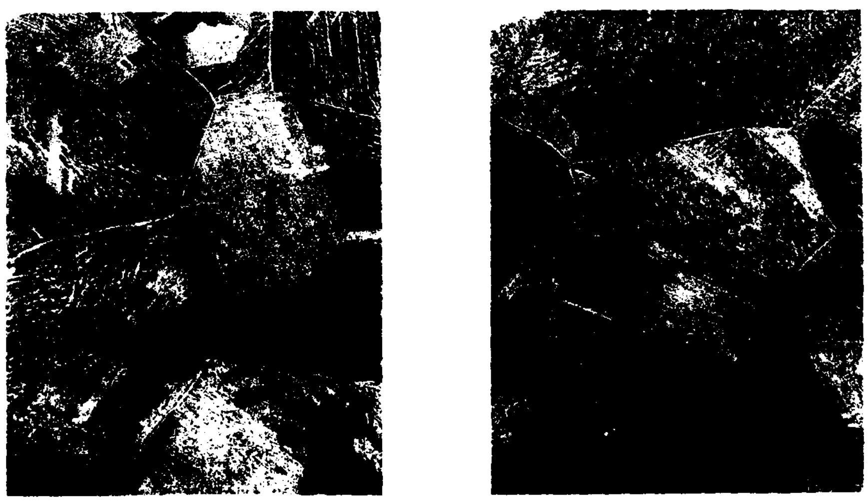


FIG. 14: MICRO EXAMINATIONS

LE FACTEUR DE FONDERIE EN QUESTION

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RESUME

Il semble que des régulations anciennes telles que :

- la FAR25 (USA)
- le DEF STAN 00970 (UK)
- AIR 2004/E (FRANCE), etc...

n'aient pas pris en compte les progrés récents réalisés dans les procédés de fonderie utilisés dans les fonderies aéronautiques, dans la gestion de production, dans le contrôle de la qualité, dans l'assurance qualité, et aussi dans la collaboration entre utilisateurs et fondeurs.

I Un rappel des progrés de la fonderie aéronautique sera fait.

II Les présupposés dans l'introduction du facteur fonderie seront analysés.

III L'obsolescence de ces régulations peut être démontrée en s'appuyant sur le processus de coulée, sa reproductibilité, sa qualification et son contrôle, et l'utilisation statistique des résultats d'essais.

EN CONCLUSION, on stigmatisera les conséquences néfastes pour le développement des performanes aéronautiques du maintien dans son état actuel de ces régulations.

INTRODUCTION

La création du facteur de fonderie "CASTING FACTOR" FAR25 a certainement créé une réaction de défiance vis à vis de la fonderie ce qui contribue fortement à diminuer le champ d'application de ce procédé. Il est à noter qu'un tel facteur n'existe pas pour les produits corroyés ce qui est peu cohérent quand on sait que les produits corroyés ne sont pas non plus dénués de certaines imperfections. Notre objectif est donc d'éclairer le prescripteur en vue de la suppression, ou la diminution, de ce facteur.

I - Evolution des procédés de fonderie, de leur maîtrise et des méthodes de contrôle

D'autres exposés ont pu montrer excellement l'évolution favorable des procédés de fonderie, des méthodes de contrôle et de l'assurance qualité, notamment dans la dernière décennie. L'introduction de l'ordinateur permettant par ailleurs un bien meilleur suivi des opérations de production et de contrôle.

Nous voudrions plus spécialement insister sur le procédé mis au point par notre société et qui a fait l'objet d'un exposé documenté au 54ème meeting AGARD tenu les 4 et 9 avril 1982 à BRUXELLES et dont ci-joint un tiré à part.

Ce procédé permet la reproduction d'une pièce à l'autre et sans intervention humaine des paramètres clefs de la coulée :

- température,
- vitesse de remplissage,
- surpression de solidification et temps de maintien.

Ces progrés n'ont toujours pas été pris en compte dans les évolutions de la FAR25.

II- Présupposés dans l'introduction du "Casting Factor"

L'utilisation de coefficients allant de 1,25 à 2 pour les pièces dites critiques suppose que :

a) - le matériau est globalement mauvais et (ou)

b) - le matériau est localement défectueux, et (ou)

c) - les dimensions des pièces et leurs tolérances ne sont pas respectées.

Cela suppose donc :

a) - que le fondeur a une méconnaissance de son procédé notamment en ce qui concerne

la coulée, le refroidissement, le traitement thermique.
A notre époque, une telle hypothèse, en considérant les capacités et l'expérience des fondeurs RAQ2, est sans fondement.

b) - qu'il existe des zones de retassures plus ou moins fines qui traduisent un incident de refroidissement local.
Si ces microretassures apparaissent en radio, c'est que la pièce nécessite un complément de mise au point. On peut les comparer à des défauts majeurs. Ces défauts majeurs existent dans le corroyé et sont tolérés jusqu'au Ø 1,2 mm en ultrasons. Or il n'existe pas en corroyé de coefficient d'abattement.

c) - que le dimensionnement des pièces n'est pas respecté en tolérances. C'est donc que le fondeur n'a pas des outillages fiables (de fabrication ou de contrôle), qu'il ne maîtrise pas la fabrication des moules et noyaux, qu'il n'a pas mis en oeuvre une méthode de contrôle statistique des dimensions qui lui permet de ne vérifier qu'un certain nombre de cotes.

Or, il serait surprenant que les outillages utilisés par les ateliers d'usinage soient de meilleure qualité que ceux utilisés en fonderie, que la maîtrise des outils de coupe soit plus assurée en mécanique que ne l'est la maîtrise des matériaux de moulage dans les fonderies aéronautiques, que les méthodes statistiques ne s'appliquent pas aussi bien en fonderie qu'ailleurs.

III- <u>Le coefficient de fonderie est superflu pour les pièces dites de "haute qualité" sur les bases suivantes appliquées par les fonderies aéronautiques</u> :

1) - le processus de coulée est figé : qualification des paramètres de coulée des pièces, enregistrement, donc traçabilité, des paramètres pour chaque pièce.

2) - le processus est qualifié par des dissections et chaque évolution de gamme est couverte par une nouvelle dissection.

3) - les critères radiographiques sont très sévères, à la limite du procédé de contrôle. Les pièces subissent des contrôles radio <u>unitairement</u>.

4) - sur la base des dissections on réalise des statistiques sur le procédé (par pièce, famille de pièces, etc...).

CONCLUSION GENERALE

L'aéronautique s'est toujours donnée comme objectif : la performance dans l'économie. Un coefficient de fonderie arbitraire va en sens contraire car il a pour conséquence :

- ou d'éloigner des solutions fonderies dont de nombreuses études ont montré l'intérêt économique,

- ou de surdimensionner des pièces, ce qui se traduit par des pièces lourdes qui nuisent à la performance générale,

- de créer un frein psychologique chez le concepteur et un manque de dynamisme chez les fondeurs,

- de décourager d'entreprendre des essais coûteux en vraie grandeur capables de vérifier des résultats de calcul forcément pessimistes.

Nous formons le voeu qu'une concertation entre concepteurs, prescripteurs, fondeurs, et outilleurs, viennent conforter les progrés de la fonderie aéronautique au bénéfice de ses clients.

QUALITY CONTROL OF CASTINGS

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SUMMARY

There is a degree of ambiguity about the word quality when applied to cast products: it can refer to the external engineering form of the casting, covering such parameters as dimensional tolerances and surface finish; or it can indicate some measure of performance expected of the cast material, such as the tensile load capability or fatigue behaviour. The need for higher quality, in both senses, is of utmost importance if castings are to compete successfully with other manufacturing routes.

Casting techniques have advanced significantly over the past 10-15 years and quality in the engineering sense is under much closer control now than it used to be. However, the internal metallurgical quality of castings has not shown the same general improvement in the same period of time, poor metallurgical quality being indicated by large "casting factors" that are applied by design engineers to load-bearing castings.

Quality systems frequently refer to "zero defect rate", whereas they really mean "zero reject rate" or "zero scrap rate". Zero defect rate, in the sense of metallurgical quality, is the absolute quality limit: this is most closely approached at the present time by squeeze casting.

INTRODUCTION

Much has been written in the past on the quality of castings and the ways in which quality can be quantitatively measured and controlled. Regrettably, the subject is fraught with confusion, inaccuracy and misrepresentation at all levels, not only because the word quality itself is open to different interpretations by different types of professional engineers, but also because castings are inherently non-uniform three-dimensional structures in which the internal microstructure is non-uniform.

The load-bearing capacity of the casting depends directly upon its microstructure, which in turn depends upon the prevailing casting conditions. Since the mechanical property attainment is a measure of the inherent quality of the casting, the goal is to be able to predict mechanical properties from alloy constitution, casting conditions and post-solidification heat treatments. The attainment of such a goal would provide castings of guaranteed metallurgical and mechanical quality. Unfortunately two factors militate against this at the present time: the first is the lack of strict process control in the foundry which allows significant variations of microstructure to arise from casting to casting; and the second is the lack of basic knowledge, even for the commonest aerospace casting alloys, of how changes in microstructure affect resultant mechanical behaviour. The current burden of this lack of proficiency impedes the wider use of castings as high integrity structural components for aerospace applications.

The imposition of punitive casting factors can only be considered to be a short-term palliative to the problems of imprecise process control and unknown microsturcture/property relationships. In the longer term, the strict application of statisitical process control will resolve the first deficiency and further fundamental research is required to eliminate the second. This present paper contributes towards the elucidation of the underlying microstructure/property relationsips of some aluminium light alloy castings of the Al-Si type.

CASTING PROCESSES AND CAST METAL QUALITY

There is an extensive range of casting processes available to transform liquid metals into near net shape components. Despite this apparently wide variety of casting techniques, all casting processes can be categorised simply depending upon whether a ceramic mould or a metal mould is used and whether or not pressure is applied as an aid to casting[1]. The selection of the mould material determines the rate of heat transport from the liquid metal, which itself governs the cooling rate, and which in turn controls the microstructural state of the casting. The application of pressure to the mould assembly during solidification can have a dominant effect on the presence or absence of porosity in the casting.

Aerospace casting alloys are commonly polyphase alloys, their mechanical properties depending both upon the spatial distribution of the equilibrium phases in the particular alloy and also on the incidence of porosity in the casting. A quality index, Q, has been proposoed in the past[2] for use with A356 and A357 alloys which relates Q directly with the static mechanical properties UTS and El% in the form:

$$Q = UTS + 150 \log_{10} El\%$$

The evaluation of Q for a particular cast component obviously requires the destruction of the casting to obtain the in situ properties. This formulation cannot be used predictively and has not been used for casting characterisation to any great extent. The two properties measured are both influenced by the internal phase distribution and by the presence of porosity, but the quantitative relationship between these microstructural features and the mechanical properties was not established independently. The various casting processes mentioned earlier all impose different solidification conditions and hence yield products having different micromorphologies and which contain varying amounts of porosity. As microstructural features have not been investigated either absolutely or comparatively, the causes of changing values of Q with casting process are not known. Furthermore, a high value of Q is only of significance if it is coupled with an elongation above the minimum requirement, often set in the region of 3%.

In order to avoid the necessity of having to perform numerous cut-up tests on production castings, the quality index formula was subsequently developed [3] in an attempt to establish an alternative quality index, Q_A, dependent only on the microstructural characterisation of the A356 or A357 alloy. Q_A was derived in terms of primary aluminium cell size, eutectic silicon aspect ratio, and the volume fraction of porosity. Although it has been claimed that the Q_A values derived microstructurally correlate closely with Q values obtained experimentally, the limited agreement found between them might be more coincidental than real. Doubts arise because of the way in which the microstructural features such as aluminium cell size and porosity were determined and averaged over the entire structure. More recent work outlined below indicates a sharp specificity between any microstructural feature and its influence on properties.

MICROSTRUCTURE/PROPERTY RELATIONSHIPS

A356 and A357 alloys

Castings for the aerospace industry are made by sand casting using either silica sand or zircon sand and by investment casting with either hot or cold moulds and filling them either in air or under vacuum. This represents a wide variety of casting conditions and microstructural variations and it is only to be expected that quality will correspondingly range widely. Depending upon the casting conditions and the precise composition of the alloy, the following microstructural characteristics will all contribute to the mechanical behaviour:

- Volume fraction of aluminium primary phase;
- grain size of the aluminium primary phase;
- secondary dendrite arm spacing of the aluminium dendrites;
- spatial distribution of the Al-Si eutectic (dependent on (a) and (b));
- refinement of the Al-Si eutectic;
- size and distribution of any intermetallic phases;
- level and distribution of porosity;
- presence and distribution of non-metallic inclusions.

Casting experiments have been made to obtain a relationship between cast microstructure and solidification conditions of certain compositions of A357. Secondary dendrite arm spacings (SDAS), eutectic silicon spacings, and silicon aspect ratios are typical parameters that are measured as a function of cooling rate. An example of the relationship between the SDAS of one particular A357 alloy and the local solidification time has been found to be of the form:

$$\mathrm{SDAS} = 8.765\ t_f^{0.35}$$

where the SDAS is measured in µm and t_f is in seconds.

The interparticle spacing in the Al-Si eutectic, λ, depends only on the growth rate of the eutectic front, R, rather than on the cooling rate of the casting as a whole. The form of the λ dependence on R is

$$\lambda^2 R = 1.43 \times 10^{-6}\ \mathrm{mm^3\ S^{-1}}$$

where λ is given in mm and R is in mmS^{-1}. The interparticle spacing decreases with increasing growth rate.

Tensile tests carried out on specimens solidified over a range of freezing rates [4] have shown a marked improvement with increasing freezing rate, as shown in Figure (1), where the results are given in terms of the quality index, Q. In fact, the decreases in UTS and elongation that are responsible for the lowering of the quality index are probably much more strongly dependent on changes in the Si interparticle spacing, λ, of the eutectic matrix than on the SDAS. This might have been expected from the observation that the fracture path of these materials predominantly follows the eutectic network. Figure (1) also illustrates the marked improvement in quality, as determined solely by static uniaxial testing, found with chemical modification treatment of the eutectic mixture with strontium additions. This result again shows that it is the eutectic matrix that determines the tensile properties, not the SDAS of the aluminium phase, since the SDAS is reasonably independent of the strontium concentration.

The effect of porosity on the tensile properties of cast alloys has always been difficult to establish. Porosity is ubiquitously present in all aerospace castings at the time of manufacture and both the size range and the spatial distribution of the porosity are usually in scale with the dendritic structure. It has recently been shown [5] that the UTS and El% are both dramatically reduced by the occurrence of porosity in A357 alloys. No correlation was observed with the average porosity level of the casting, but a direct dependence was discovered on the length of the largest pore present in the test specimen. Figures (2) and (3) show the results and illustrate the severity of the problem of porosity. These data have been re-analysed in terms of the decrease in quality index, Q, with the size of the largest pore and the results are presented in Table 1. Extrapolating the data to zero defect size, the ultimate level of quality for this set of A356 castings is found to be Q = 554. For castings produced over a range of cooling rates but containing the same range of defect sizes, one might expect a series of lines that were parallel or nearly parallel to those drawn in Figures (2) and (3), with the ultimate level of quality increasing with increasing refinement of the microstructure.

Figure (4) shows the influence of increasing amounts of iron on the quality index [4], reflecting the well known deleterious effects of iron on the tensile properties of aluminium-silicon alloys. It is known, however, that it is not the absolute level of

iron that is important but the size and spatial distribution of the FeAlSi intermetallic compounds. Results to be presented later show that Al-Si alloys containing over 1% Fe can have remarkably good properties if the iron is properly dispersed throughout the microstructure.

The data presented so far are derived from static tests and the derived quality index figures refer only to uniaxial tensile tests. In reality, however, load-bearing aerospace castings will suffer dynamic stressing and therefore dynamic loading experiments will be much more searching tests of quality and of much greater relevance to service behaviour than are the static tests.

Surprisingly little work has been performed and/or published on the fatigue behaviour of A357 alloys. Figure (5) displays the results (6,7) of fatigue tests conducted on A357 material produced by three different casting processes. The rates of freezing of the three sets of castings were not measured, but both the Howmet V^2 process and the sand casting process are inherently slow freezing processes compared with chill casting. The fatigue properties of the Howmet alloy are apparently better than those of the other two castings even though the Si particle size is greater in the Howmet casting than in the chill cast material. This difference could be due to the greater level of porosity in the chill cast alloy or to the different fatigue test R values. The sand cast alloy, containing even greater amounts of porosity and having a coarser microstructure exhibits the lowest fatigue curve. Sand cast-plus-HIP material would be expected to have similar fatigue properties to those of the Howmet alloy. Similarly, peening the surfaces of the fatigue specimens of the chill cast and sand cast materials gave significant improvements to the fatigue behaviour, the best of the peened chill cast material being as good as the Howmet material.

Fracture toughness testing of A357 alloys has recently been conducted in the author's laboratory using three-point bend tests and the double torsion technique. K_{IC} values in the region of $25MPam^{\frac{1}{2}}$ were obtained for as-cast material produced in sand moulds. For chill cast specimens an increased value of $\sim30MPam^{\frac{1}{2}}$ was found. An even higher value of K_{IC} of $\sim35MPam^{\frac{1}{2}}$ was measured for the same material squeeze cast in a metal mould. These results, shown in Figure (6), indicate that the toughness increases as the microstructure becomes more refined as the applied cooling rate is increased. Increasing the freezing rate decreases the SDAS of the primary aluminium phase: it also refines the silicon phase of the eutectic and promotes a change of morphology from flake to fibrous, as does strontium modification. Specimens having a fibrous eutectic morphology have values of fracture toughness generally higher than those that are unmodified. For instance, for a slowly cooled Sr-modified alloy the measured K_{IC} value was $\sim33MPam^{\frac{1}{2}}$, implying that the increase of some $8MPam^{\frac{1}{2}}$ was due solely to the refinement of the eutectic Si phase and not related to the SDAS of the aluminium primary phase.

In an attempt to isolate the influences of the two separate phase distributions in A357 alloy, the fracture toughness was determined independently for the primary aluminium phase, for which K_{IC} was $\sim55MPam^{\frac{1}{2}}$, and for the eutectic mixture in various microstructural configurations, for which the values of K_{IC} are given in Figure (7). Obviously the fracture toughness of the A357 alloy is determined by a combination of the properties of the primary aluminium dendrites and the eutectic constituents and also on their particular spatial distributions. The obvious advantage of strontium modification is clearly shown in Figure (7) but the very high fracture toughness values of both the primary phase and the eutectic structure, particularly the modified eutectic, are not achieved in the A357 alloy itself, as is apparent from Figure (6). This means that the fracture toughness of the A357 alloy is less than would be expected from the sum of the proportionate fracture toughness values of the aluminium primary phase and the eutectic mixture. The reason for this is not understood.

Summarising the above results, it is apparent that the mechanical properties of A356 and A357 alloys are extremely sensitive to the imposed casting conditions. In particular, both the static and dynamic mechanical properties increase with increasing freezing rate or with chemical modification of the eutectic structure. The quality index, Q, is, in itself, of limited value as it possesses no predictive power to indicate the mechanical resistance of the alloys to alternating stress. Furthermore the effect of porosity, which has the major effect on fatigue behaviour, is not treated separately as an independent variable. The alternative quality index, Q_A, attempts to quantify the effects of microstructure on mechanical properties: to date, however, only average effects of the salient microstructural parameters have been used (3) whereas it is known(5), in fact, that certain mechanical properties are very defect specific. It appears, then, that the approaches to assessing the quality of castings by a generalised quality index are not, for the present at least, sufficiently well-established to be of any assistance in advancing the status of castings very far.

One of the greatest obstacles to the further improvement of cast metal products which would increase their utilisation is the lack of knowledge of the absolute properties that are attainable with the cast material. Small improvements in mechanical properties have been obtained slowly over the years by changes in casting practice and by using progressively higher purity charge materials. However, most castings inevitably contain defects of a size equal to the grain size of the cast alloy and it is only within the past five years that the real influence of these defects on mechanical properties has been established quantitatively. This new body of knowledge has come from using squeeze casting and some of this recent work is outlined in the following section.

SQUEEZE CAST Al-Si ALLOYS

Squeeze casting is the name given to the recently commercialised casting process in which metal is solidified under the direct action of pressure sufficient to prevent the appearance of either gas porosity or shrinkage porosity. Squeeze casting is unique in this respect: all other casting processes leave some residual porosity. The process is also known

variously as liquid metal forging, squeeze forming, extrusion casting and pressure crystallisation.

The combination of high pressures and metal moulds leads to higher heat transfer coefficients in the squeeze casting process than those appropriate to sand casting and gravity casting. The most obvious manifestation of the higher heat transfer coefficients is a general and marked refinement of microstructure. Studies have been made on the microstructures of pure binary Al-Si alloys cast under atmospheric pressure in a metal mould and squeeze cast under a pressure of 150 MPa. There is no change in the proportion of phases present but there is an obvious change in the phase distribution and microstructural refinement.

Several different commercial alloys have been squeeze cast and their mechanical properties have been assessed and compared with those of the sand cast and gravity cast material of the same composition. Table II gives the typical mechanical properties of LM24, LM25 and A357 cast by the different techniques and tested under a variety of heat treatment conditions. The compositions of these alloys are listed in Table III. It is clear from the figures given in Table II that significant improvements in properties can be achieved when the commercial alloys are squeeze cast. For A357 both the UTS and the El% are improved. The greatest advantage with squeeze casting is found for the less pure and less expensive LM24 and LM25 alloys. Of particular significance is the effect of strontium modification on the LM24 alloy in its fully heat treated condition, increasing the El% from 2% to 5%. The lower values of El% for LM24 compared with LM25 and A357 is probably accounted for by its higher silicon level. It is particularly noteworthy that the cheap Sr-modified LM24 alloy can provide better mechanical properties than the more expensive LM25 and A357 alloys when they are squeeze cast and fully heat treated. Indeed, for LM24, which is normally considered to be non-heat treatable, the fully heat treated squeeze cast material exhibits a 0.2% proof stress three times higher and a UTS over twice as high as the specified standard requirements. By using the squeeze casting technique the usually deleterious iron aluminide crystals do not grow into massive plate-like forms but are very small and uniformly dispersed throughout the matrix and hence do not exhibit their usual embrittling effects. That is, by manipulating and controlling the microstructure it is possible to transform the lowest quality LM24 into an alloy capable of exhibiting premium quality properties. In this particular case the alloy is approaching its ultimate achievable properties for a cast component. It appears that the A357 produced under good investment casting practice with strontium modification is also near to the limit of its ultimate properties.

It has been found that the squeeze cast materials also exhibit dynamic properties superior to those of the conventionally cast materials. Figure (8) shows the fatigue properties of the three alloys from which it is evident that squeeze casting the A357 increases its endurance limit by approximately 80 MPa over the sand cast figure. This improvement is due both to a refinement of the eutectic silicon phase and to the total absence of porosity, although insufficient research has been performed to determine which of the two factors is the dominant one. There is undoubtedly scope for improvement of the fatigue properties of A357 by eliminating all the porosity during the casting process instead of by subsequently HIPing the cast product. Figure (8) also shows that, remarkably, the fatigue curve of the squeeze cast LM24 alloy is 40-50 MPa higher than that of the squeeze cast A357 alloy despite its having an iron concentration of over 1%.

Squeeze casting yields material of optimum microstructure having optimum mechanical properties. The rate of cooling is rapid, the microstructure is refined and after full heat treatment the properties are as good as they can be for the cast material. All other casting processes produce material of inferior properties and hence of inferior quality. For A357, the static properties of well produced investment cast material can be extremely good and approaching the ultimate. The dynamic properties are not so good and are improved by HIPing. Low pressure sand casting (8,9) decreases the amount of porosity in the A357 and the dynamic quality of material produced by this casting technique is superior to that of the investment cast material, as is the static quality. Table IV lists the typical values of static mechanical properties of A357 produced from a range of casting processes: the quality of the material improves on progressing down the list.

The attainment of ultimate properties has to be compromised to a certain extent, of course, due to the applied constraint of casting complexity. Intricate shapes cannot be made at present by the squeeze casting process and therefore industrially realisable casting shapes for the aerospace industry will continue to be manufactured via some sort of ceramic mould technique. By and large, ceramic mould techniques used together with applied pressure produce better quality castings than alternative processes not using pressure. Further developments in this field will no doubt be made and improved processing will yield improved quality. The other major area of improvement that will undoubtedly feature prominently in the future will be the respecification of current alloy systems and the development of new alloys to new specifications. It cannot be assumed that the alloys that are in use now are the best alloys available. Not only will minor additions of alloying elements improve the cast metal quality of known alloy systems, such as has happened with the addition of strontium to A357, but significant changes to the major alloying elements can also be envisaged. Much more research is needed in the microstructure/properties area to make these improvements materialise and it is very probable that major benefits will accrue when these new alloy compositions are linked more closely with specified casting processes.

CONCLUSIONS

This report has stressed the overriding importance of microstructure on the properties of cast A356 and A357 alloys, and several simple conclusions can be drawn.

- For most casting processes the dynamic properties can be enhanced by a post-solidification HIPing treatment which removes the most damaging defects in the casting, viz, the porosity.
- Results also show that the coarseness of the microstructure also strongly influences the static and dynamic properties of the cast material.
- The dominant microstructural feature is not the secondary dendrite arm spacing but the interparticle spacing of the eutectic silicon phase.
- In general, modification of the eutectic structure by chill casting or by the addition of strontium promotes a marked improvement of the mechanical properties of the alloy.

These simple statements are made on the basis of very little experimentation, the availability of very limited data, and in the total absence of any comprehensive and comparative study of the properties of A356 and A357 produced by different casting processes. Furthermore, the data presented have not been obtained under constant mechanical experimental conditions and therefore any variation witnessed might be the result of variations in testing techniques. For instance, fracture toughness testing following ASTM guidelines requires very large cast specimens to ensure plane strain testing conditions. However, the microstructural parameters of ceramic mould cast metals scale as the square of the casting dimension and since mechanical properties, including the fracture toughness, are sensitive to microstructural dimensions, the testing of thick section test pieces provides only an inappropriate lower limit for the fracture toughness of thinner section castings. It has been shown (10) that the three-point bend test and the double torsion technique provide very good estimates of the plane strain fracture toughness of A357: that being so, the values given in the present paper have been labelled K_{IC}. The testing of aerospace castings of different section thicknesses and different micromorphologies ought not to be inhibited by standards that were devised initially for thick steel plates of uniform microstructural condition. Similarly, the assessment of the tensile properties of a casting from the measured properties of a separately cast test bar will be of limited value unless the microstructure of the test bar is the same as that of the casting it is supposed to represent. In any event, individual castings are rarely of a constant section thickness and an inherent variation in properties will almost inevitably be engendered.

Although it is attractive to generate quality index figures based on either static testing or a combination of static testing and microstructural analysis, the results of such computations are not directly transferable to dynamic conditions and to actual practical performance. The broad correlation (7) between tensile strength and fracture toughness found over a range of aerospace alloys cannot be taken too far because for each particular alloy composition there is an inverse dependence between fracture toughness and tensile strength. It would appear that at the present time no one parameter will accurately describe the quality of a cast material in a way that has immediate predictive utility and design applicability.

As a final conclusion, echoing what was stated at the beginning of this paper, it is clear that the only way forward is to further investigate the microstructure/property relationships in these aerospace alloys over a wide range of controlled microstructural conditions and to assess each mechanical property thoroughly as a function of phase distribution and alloy content. That is, as much research effort must be invested in cast aerospace materials as is invested in their wrought counterparts in order to obtain the required basic understanding that is necessary before absolute confidence can be placed in cast structures.

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Table I

Pore length (mm)	1	2	3	4	5
UTS (MPa)	330	315	310	300	287
% Elong.	16.6	12.6	8.8	5	1.8
Q.	513	480	452	405	325

Table II

		0.2% proof stress (MPa)	UTS (MPa)	Elongation (%)
LM24	minimum requirement	100	180	1.5
	typical chill cast	110	200	2.0
	squeeze cast (as-cast)	126	233	2.7
	squeeze cast (F.H.T.*)	330	368	2.0
	squeeze cast Sr-modified (F.H.T.)	315	393	5.0
LM25	typical chill cast (as-cast)	90	180	5
	squeeze cast (as-cast)	104	214	5.3
	typical chill cast (F.H.T.)	240	310	3
	squeeze cast (F.H.T.)	274	331	7
A357	Typical chill cast (F.H.T.)	248	313	7
	squeeze cast (F.H.T.)	283	347	9.3

*F.H.T. = Fully Heat Treated

Table III

	Si	Cu	Zn	Mg	Mn	Fe	Ti
LM24	7.5-9.5	3-4	3	0.1	0.5	1.3	0.2
LM25	6.5-7.5	0-1	0.1	0.2-0.45	0.3	0.5	0.2
A357	6.5-7.5	0.05	0.05	0.45-0.6		0.15	0.2

The figures are the compositions in wt.%
Single figures are maxima

Table IV

Properties of 357 aluminium alloy
obtained with various casting processes

A357	0.2% proof stress (MPa)	UTS (MPa)	Elong %	Q
sand cast	200.6	226.6	1.6	257
chill cast	248.6	313.6	6.9	439
Cosworth	242	312	9.8	460
squeeze cast	283	347	9.3	492

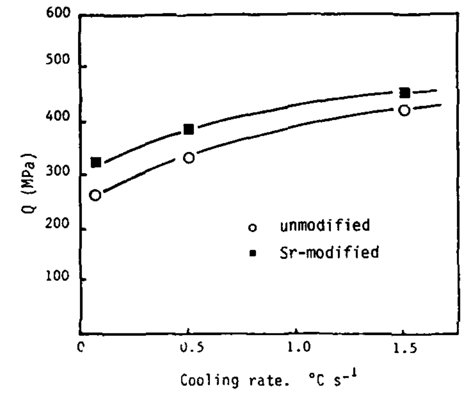

Figure 1. Quality index as a function of cooling rate for A357 alloy.

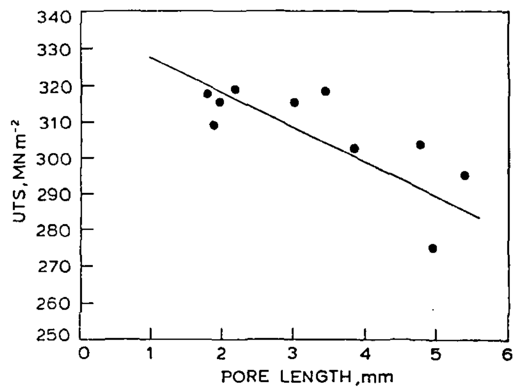

Figure 2. Ultimate tensile strength of A357 as a function of maximum pore length

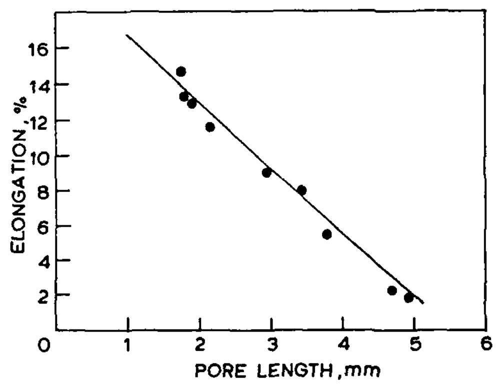

Figure 3. Elongation to fracture of A357 as a function of maximum pore length.

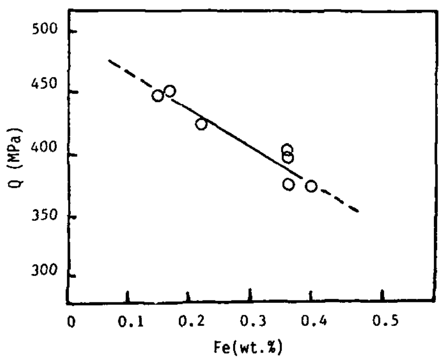

Figure 4. Quality index of A357 as a function of iron content.

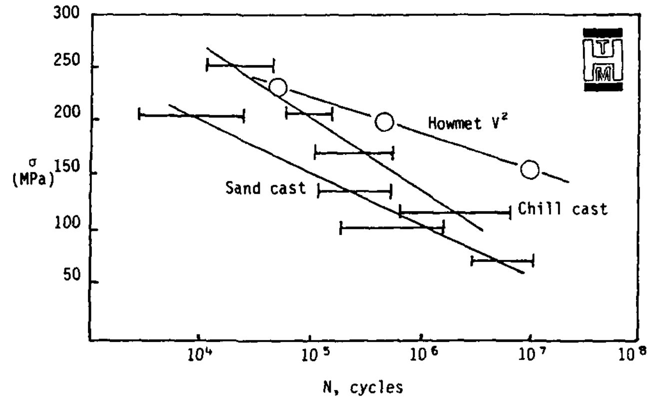

Figure 5. Fatigue curves of A357. For the Howmet data R = 0.1; for the other data R = -1.

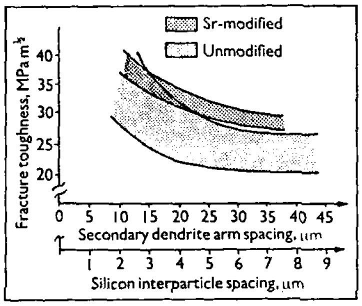

Figure 6. Fracture toughness of A357 alloy in castings solidified over a range of cooling rates, with and without Sr modification

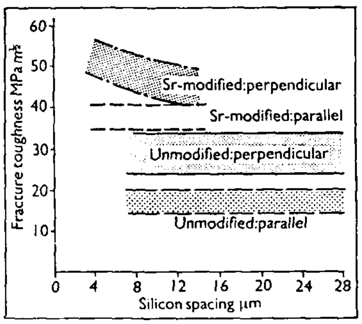

Figure 7. Values of K_{IC} for Al-Si eutectic alloys as a function of orientation for modified and unmodified alloys. Parallel and perpendicular refer to the direction of crack propagation with respect to the growth axis of the Si phase

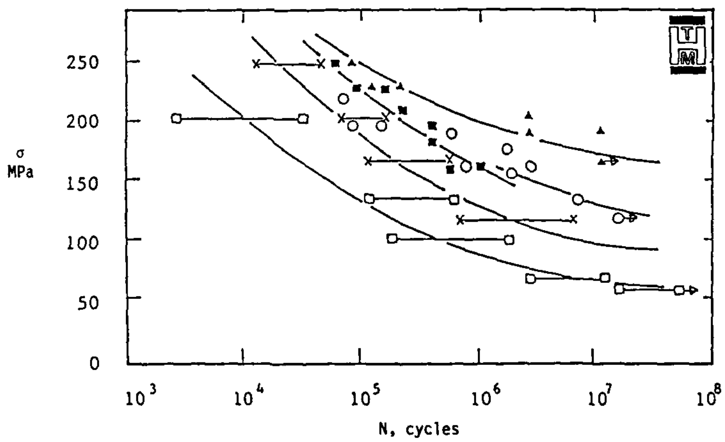

Figure 6. Fatigue behaviour of cast aluminium alloys
□ sand cast 357; x chill cast 357;
o squeeze cast LM25+1.25 Cu; ■ squeeze cast 357;
▲ squeeze cast LM24

COMBINED ADVANCED FOUNDRY & QUALITY CONTROL TECHNIQUES TO ENHANCE RELIABILITY OF CASTINGS FOR THE AEROSPACE INDUSTRY

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Summary

This paper deals with some aspects of the technological innovation which can contribute, when fully inserted in the productive process, in improving the reliability of castings for use on aircraft.

They concern:

- the development of processes and the use of means to ensure the absolute repeatability of the critical items with regard to the metallurgical condition of the castings:

  . mould filling hydraulics and thermal state of the casting
  . computer assisted management of specific chills
  . quality of liquid metal
  . quenching conditions;

- computerised quality control systems which guarantee systematic control of the qualitative conditions of the castings and non-destructive testing systems ensuring an adequate level of reading the internal soundness at acceptable costs (radioscopy linked to image processing systems and high-resolution equipment).

INTRODUCTION

The potential advantages related to the use of structural components of cast aluminium compared to other alternative technologies are widely acknowledged in the field of aeronautics:

- the possibility of complex shapes and lighter weights otherwise unachievable with the maximum degree of freedom in design;

- minimization of the components needed to produce a determinate assembly, with heavy reduction of the number of items to be handled;

- mechanical machining can be reduced to a minimum through effective dimensional inspection and accurate reproduction of the contours.

In actual fact, the capability to achieve an excellent compromise between weight and cost has not yet been translated into applicative developments to the extent that would be justified by the potential of the advantages that can be attained.

Among the causes that have limited the development of structural components that can be obtained through casting, particular mention should be made of the lack of trust in foundry-work as a technology capable of giving the same performances as forging or mechanical machining from blanks as far as reliability and repeatability of the mechanical properties are concerned: which entails the adoption of high super-coefficients of safety (known as the casting factor) in design, and heavy costs of non-destructive tests.

We are of the opinion that these factors which today strongly restrain the role of the foundry as a technology capable of providing a determinant contribution in reducing the costs of the end product (this significance is even higher as the production volumes involved increase) can be overcome or heavily limited through an integrated approach concerning:

- the development of processes and the use of means to ensure the absolute repeatability of the critical items with regard to the metallurgical condition of the castings,
- computerised quality control systems which guarantee systematic control of the qualitative conditions of the castings and non-destructive testing systems ensuring an adequate level of reading the internal soundness at acceptable costs.

This paper shows certain aspects of the technological innovation which, in our opinion, have contributed or can contribute when they are fully inserted in the productive process, in improving the reliability of castings for aerospace in the previously mentioned ways.

Such techniques containing higher or lower degrees of innovation have been developed within our company in strict connection with the current production processes, from which they receive constant feedback about variables that are critical in terms of repeatability.

It is clear that the innovative factors mentioned are applied specifically to certain stages of production, therefore they should be regarded as perfectly integrated within the quality control procedures.

The most qualifying points of this integrated approach are the following:

- COMPUTER ASSISTED MANAGEMENT OF SPECIFIC CHILLS

In the fabrication of quality castings for aerospace the use of specific metal chills for each position in the mould is determinant; this is to avoid unevenness in cooling between one casting and another, in addition to geometric discordance.

Hence, the need arises to manage a considerable amount of different configurations. involving various technical and manufacturing departments, in order to provide complete sets of chills to the moulding area.

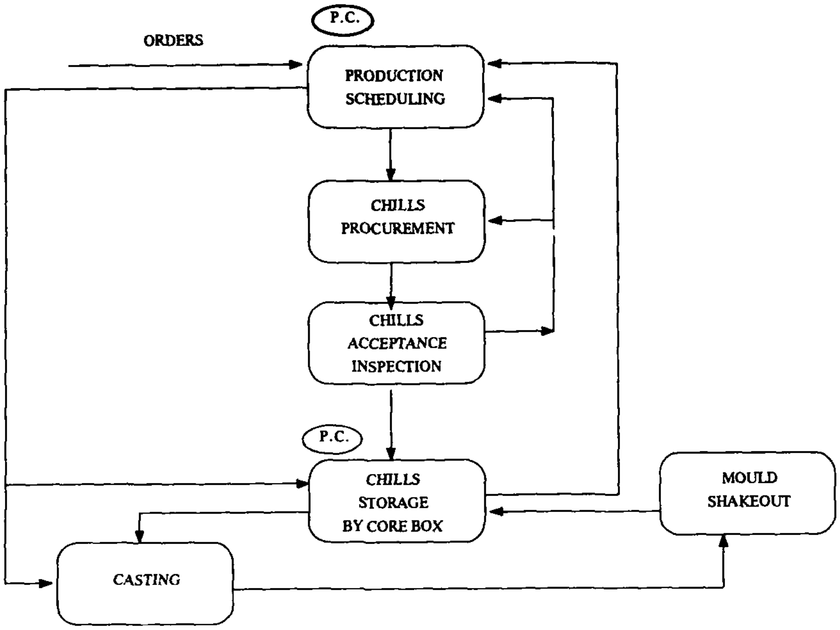
The computer gives a determinant help in managing the stores, patterns and re-organization in relation to the production programme.

In order to bring this system into operation the chills had to be coded according to a procedure that acknowledges the corebox as the base unit of the equipment, while a progressive number locates each chill inside the corebox. Hence, leaving out of consideration the drawing number of the part to which the chill is applied, thus achieving independence from the frequent variations that often occur during the life of a casting.

Therefore, each core box is given a symbol of 3 alphanumeric characters chosen at random; all the pattern-chills relating to that core box will bear the chosen symbol, in addition to a progressive number specific for the chill (e.g. A3B-12). Obviously the symbol is marked clearly on the single core box.

The simplified block diagram shows the connections between the different departments involved in handling the chills, showing the positions in which the computer can be of valuable aid (Fig. 1).

Fig. 1 - COMPUTER ASSISTED MANAGEMENT OF SPECIFIC CHILLS



- QUALITY AND REPEATABILITY OF THE METAL

Besides the normal controls on the chemical composition of the alloy and the level of refinement and modification, a determinant factor concerning the success of the casting is the maintenance of extremely low and constant hydrogen levels. This is achieved by us through degassing of the metal under vacuum.

It is not a really innovative procedure but it is held to be of fundamental importance in guaranteeing a repetitive quality in class 1 castings, especially if the wall thikness is very low; in these instances a higher than average pouring temperature is usually required and also minimum porosity levels can be determinant with regard to pressure tightness or mechanical properties.

The operational experience carried out through systematic control of the H_2 content in liquid metal shows that the reliability of this treatment is greatly superior to other methods employed currently in aluminium foundries.

A statistical survey over one year shows a much smaller dispersion of values in the case of degassing under vacuum as compared to treatments using nitrogen and hexachlorethane (Fig. 2).

Another factor held to be of considerable importance with regard to guaranteeing repeatability of the quality of the casting consists in maintaining the percentage of the single elements of the alloy within a much smaller range than that allowed by the standards for a certain alloy.

This is particularly important for Mg and Fe in Al-Si alloys, as the slightest variation of them causes alterations to the mechanical properties of the casting. Tests have proved that it is easily possible to maintain the percentage of the element within a range of $\pm$ 0.03%.

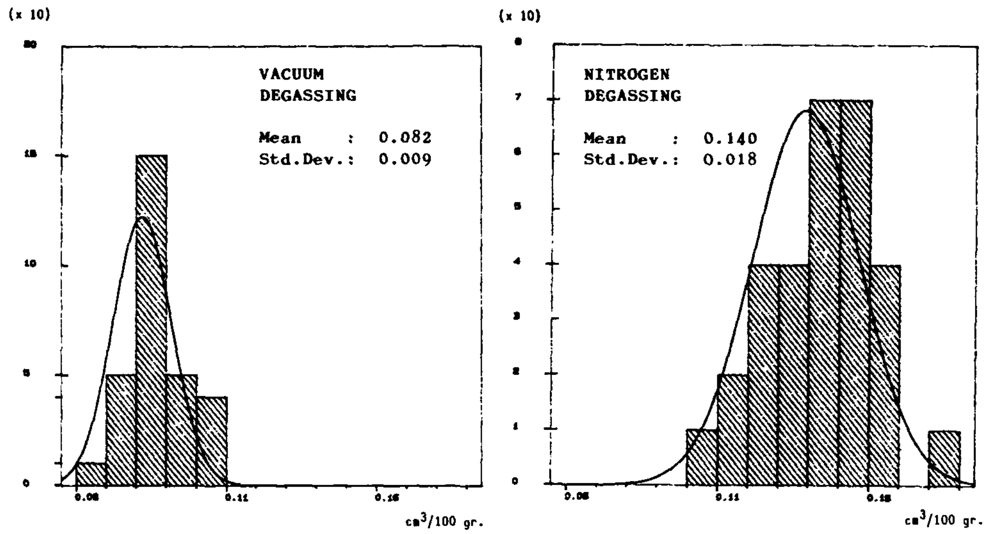


Fig. 2 - Statistical comparison between vacuum and Nitrogen degassing

- MOULD FILLING HYDRAULICS AND THERMAL STATE OF THE CASTING

During the development of castings of complex configuration, the availability of thermal charts giving an idea as accurate as possible of the solidification process is particularly helpful to the foundry engineer. This is in order to intervene where solidification is not directional often causing shrinkage or porosity.

The thermograph (Fig. 3) is an automatic temperature detection system working by means of thermo-couples inserted in the sand mould before pouring in predetermined positions in order to obtain full information concerning the thermal state of the casting. The thermo-couples are connected to a data acquisition system which is able to realize 10 readings per second per each line.

The system is equipped with a personal computer that stores the tests and also processes the characteristic points of the actual curves, giving informations on grain refinement and modification (Fig. 4).

The thermograph enables also a practical check of the correct calculation of solidification conditions, which is usually performed by mathematic models. Obviously the equipment is just as useful for process control during production, enabling the repeatability of the thermal maps to be checked in relation to the master.

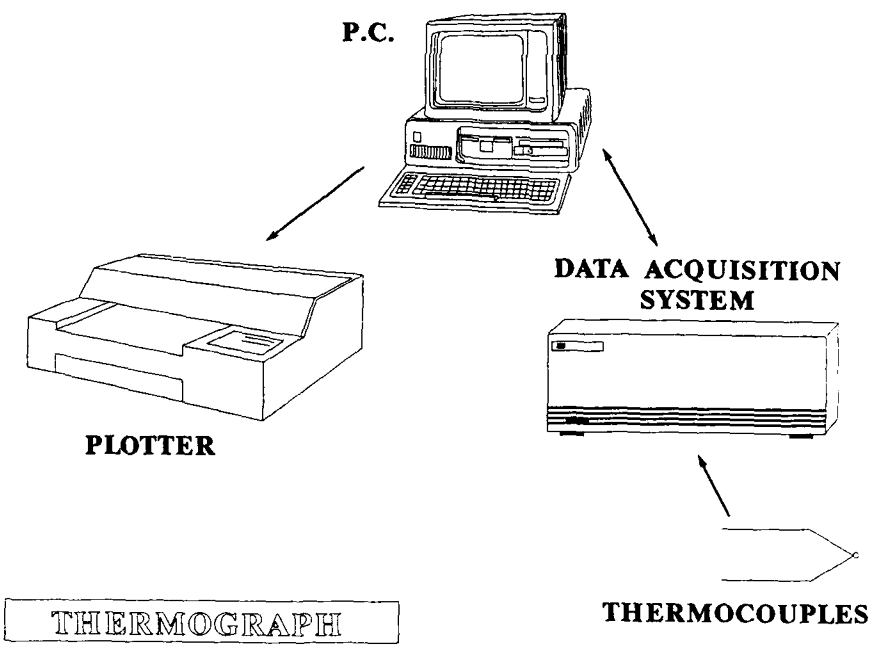


Fig. 3 THERMOGRAPH

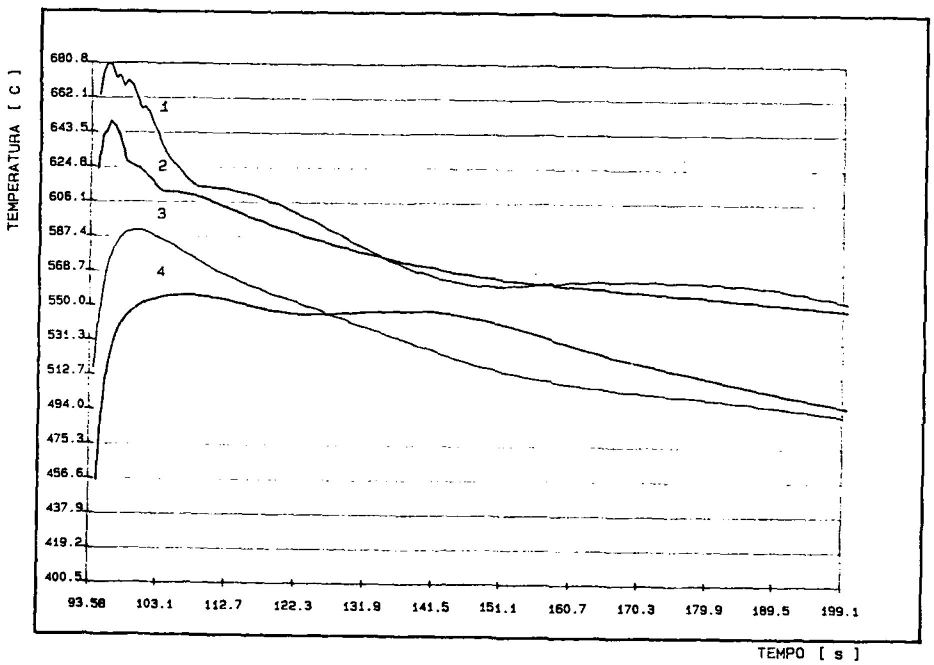


Fig. 4 - Example of solidification curves obtained by THERMOGRAPH

- **HEAT TREATMENT WITH QUENCHING IN WATER-GLYCOL**

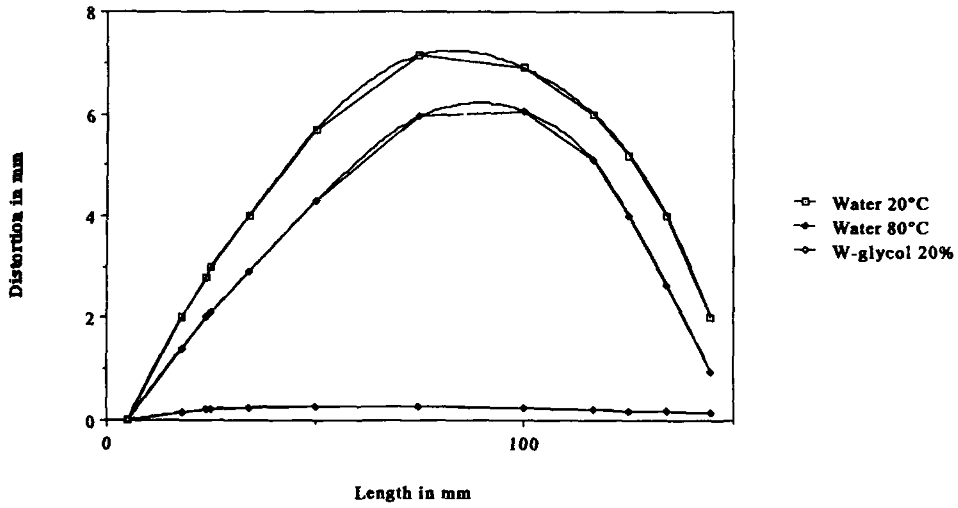
Much progress has been achieved in the field of heat treatments to warrant better precision and more accurate uniformity of the furnaces; but the quenching process is still a greatly variable factor. This is typically done in cold or hot water and the formation of steam is difficult to keep under control and is especially variable according to the composition of the batch and the position of the casting in the box.

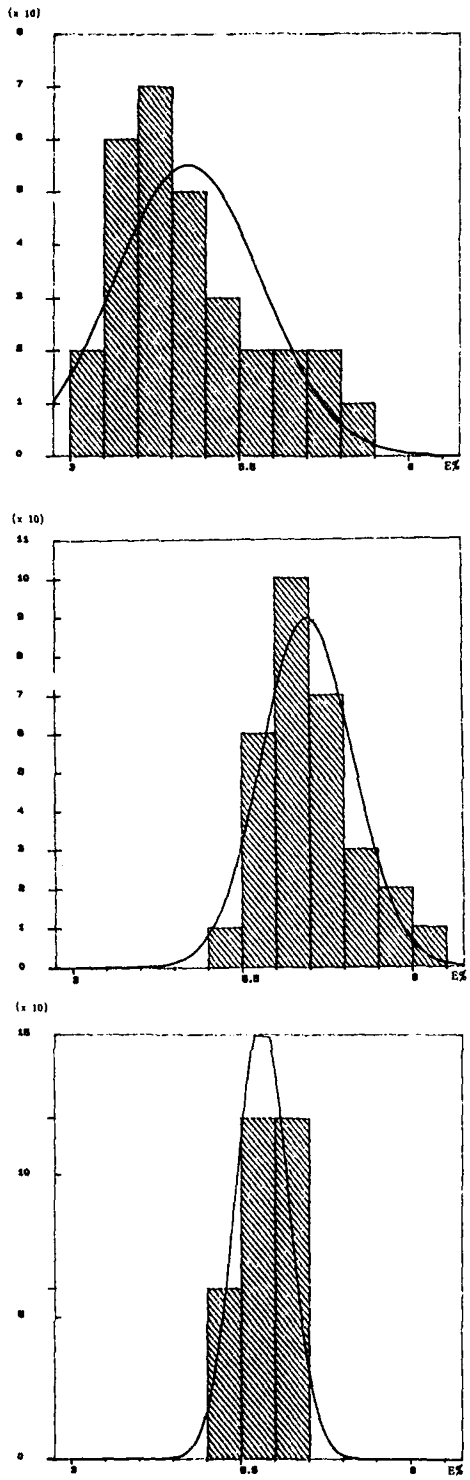
Decidedly positive results have been achieved using water-glycol mixtures with concentrations varying between 15 and 20%. The water-glycol mixture is already widely employed for quenching rolled and forged pieces and has recently started being used for the treatment of aluminium castings.

In addition to the typical reduction of deformation on thin-walled structural castings (Fig. 5), experiments carried out on engine components have shown improved repeatability of the mechanical properties, especially elongation, in comparison to cold and hot water quenching followed by overaging (Fig. 6).

This heat treatment condition is usually required for castings working at high temperature for long times in order to avoid volume deformation of the material. Dimensional findings on standard specimens that had been subjected to the same heat treatments showed a slightly reduced volume expansion in the water-glycol quenching condition.

Fig. 5 - **QUENCH DISTORTION OF ALUMINUM TEST PLATE (150x100x1.5 mm)**





HOT WATER QUENCHING (70° C)

Mean : 4.733
Std.Dev.: 1.086

COLD WATER QUENCHING

Mean : 6.467
Std.Dev.: 0.668

WATER-GLYCOL QUENCHING

Mean : 5.806
Std.Dev.: 0.384

Fig. 6 - Statistical comparison of Elongation values with different quenching conditions.

Sand cast specimens - T61 condition.

- **COMPUTERISED QUALITY CONTROL SYSTEMS**

The concepts of reliability and repeatability are strongly linked to the knowledge of the conditions of the casting in short times.

Basicly, all the written documents needed for the conduction of operations must be available to *manufacturing and* inspection operators: we mean test instructions, process standards, technical charts.

However, such preventive measures cannot be separated from the information on the actual state of the product, with regard to the single operations and the summary of historical data, showing the significant trends for all the parameters concerning quality acceptance.

In the past, these informations were collected as manually written records, certified by signatures and stamps of the operators, on the cards following the castings during their manufacturing cycle. If statistical elaborations were needed, the requested informations had to be collected starting from each record, treated and analysed.

A basic result in improving reliability and timeliness in data collection and elaboration has been achieved designing and installing in Getti Speciali foundry a computerised system: it consists of *nine terminals* installed in the shop and two in the offices (quality and production control).

The terminals on the shop floor receive informations on the state of each casting, as a result of manufacturing and *control operations*.

The Hardware and Software employed have been selected with the particular aim of simplifying communications between the operator and the system as much as possible: in *fact*:

- Input to the system takes place by reading bar codes containing the identification data of the casting and the name of the operator.
- The informations insertion procedure is mainly structured in the enquiry mode and is without *redundancies*: this means that the answers to all the informations needed are asked to the operator by the system and, since the most probable answer is taken for granted, the operator is only interrogated on *the existence of exceptions*.

The shop floor terminals are located in such a way as to guarantee immediate interchangeability *in the case of failure* and to cover the whole pouring, intermediate and final inspection areas.

The office terminals can display the following computer outputs:

- progress of the casting in the manufacturing cycle: its position (last operation and next one to be executed) and quality level (results of control -good, reject, to be *repaired*, withheld/waiting for MRB decisions - number, type and position of defects, *if any*);
- processing of parameters concerning the state of the quality of a part number and trends of more general parameters (such as *chemical compositions* and mechanical properties) and their correlations. Are hence obtained statistical representations of defects appearance (Fig. 6 for example), histograms (Fig. 7 and 8), correlation *diagrams* (Fig. 9).

Finally, this type of system allows deviations from the *specified quality* standards be located extremely rapidly and completely reliably; and coordinated, timely interventions upon discrepancies can be carried out at once when they are found to be statistically *significant*.

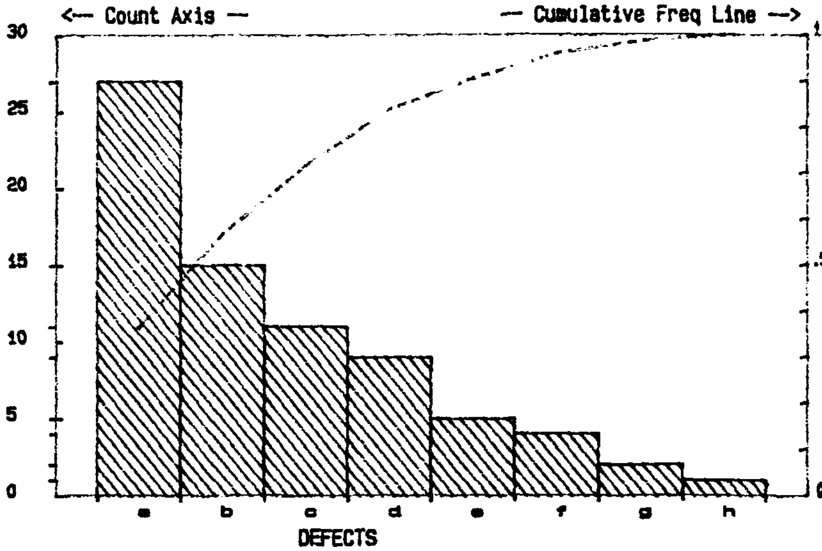
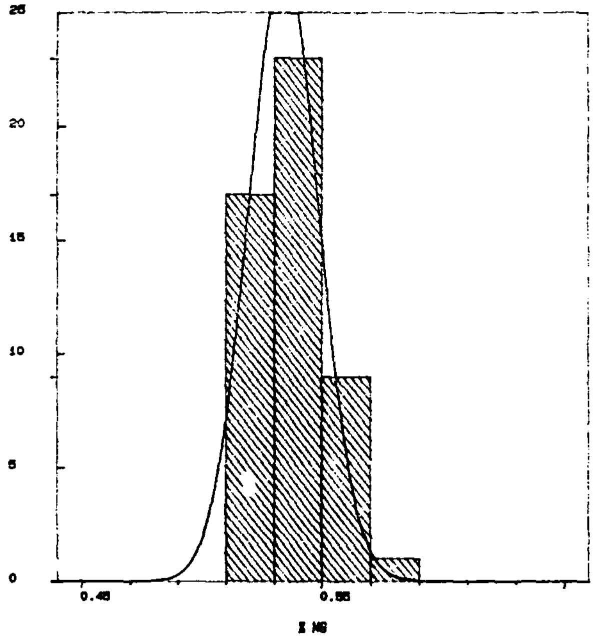
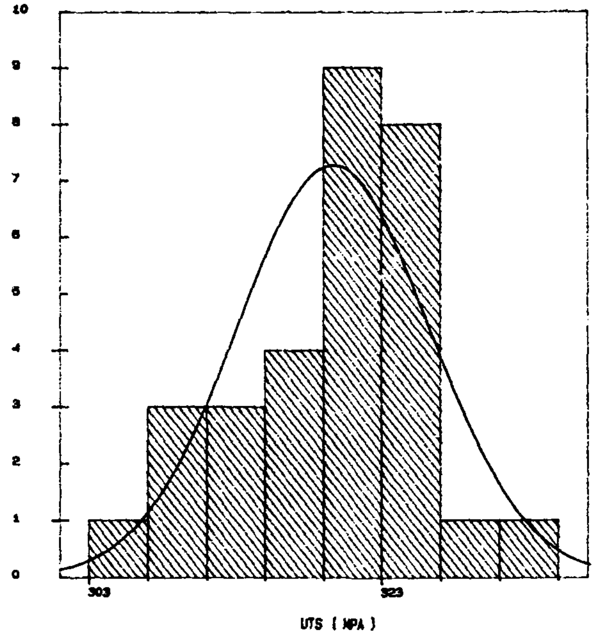


Fig. 6 - Example of PARETO chart describing frequency of defects appearence



Average value : 0,534
Std. dev. : 0,0147

Fig. 7 - Histogram showing % of Mg checked in A357 alloy



Average value : 319,6 MPa
Std.Dev. : 6,58

Fig. 8 - Histogram showing UTS checked on separate bars for A357 T61 alloy

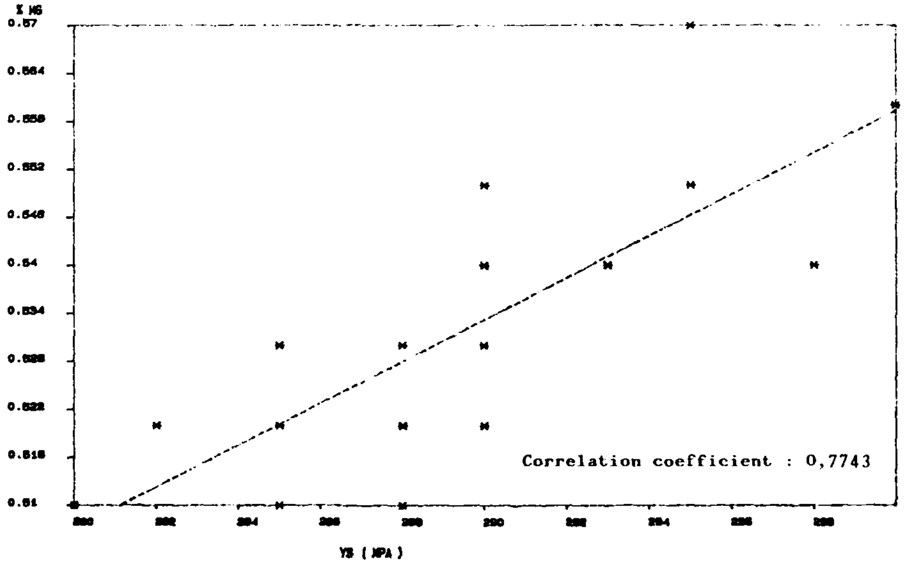


Fig. 9 - Example for correlation diagram showing yield strenght VS/ % Mg in A357 T61 alloy

THE CREATION OF QUALITY –
NEW DIRECTIONS IN THE PRODUCTION OF AERONAUTICS CASTINGS

by

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Summary

In order to ensure good consistent quality in aeronautics castings, it is necessary to introduce new quality control systems into production and inspection.

To meet the constantly rising demands of the aircraft industry, the foundry must come considerably closer to the standard of "reproducible quality". The challenge is: to plan and create quality, instead of merely inspecting it.

The general requirements - safer, faster, more economical - conceal the extremely exacting demands which the engineer and the technician have to face.

Today's foundry industry is called upon to produce more and more compact castings with ever decreasing wall-thicknesses. Components which used to be rivetted or milled, should and must, as far as possible, be cast.

The increasing refinement of calculating processes and the use of new materials constantly lead to new advances in lightweight construction.

The metallurgical quality of our castings has to conform to stricter standards, as the demands of static and dynamic loading have risen. The statistical reliability of castings must be greatly improved.

New alloys, moulding processes, casting techniques, controlled and guided solidification and heat treatments are forcing the foundry engineer to apply an increasing measure of process control.

Placed under one heading, all these individual demands mean the same thing: create quality instead of inspecting it, as is still often the case.

What improvements have there been in the last few years?

In the production of aeronautics castings, the usual practice is to ensure their quality by means of an extensive system of quality control.

- raw and auxiliary materials are subjected to incoming inspection,

- periodic checks are carried out on tooling, machines, furnace equipment measuring devices and other supplementary materials,

- the production process is accompanied by intermediate test and inspection operations at fixed intervals,

- the effectiveness of inspection operations during and after production is verified by quality control through regular audits.

In recent years, new test methods have been developed and introd[illegible] order to ensure a consistent level of quality. Examples of these are the use of [illegible] analysis in melt monitoring and image intensifying in X-ray testing.

Decisive changes have also taken place in moulding techniques. Today, the production of aeronautics castings makes use almost exclusively of cold setting resin binders. Some areas of casting production have changed over to the precision casting process, i.e. to investment casting. At the same time, the low pressure sand casting process has been developed and brought into use for castings formerly made in the conventional sand casting process. With regard to wall-thicknesses, dimensions and manufacturing costs, the low pressure process is placed between the conventional sand and investment casting processes. Good mechanical and metallurgical properties can be achieved by guided solidification and improved feeding techniques.

Increasingly high grade pattern equipment is now being used due to close tolerances with regard to dimensional accuracy and consistency. In view of these requirements, wooden patterns can now no longer be used. Only plastic and metal materials are capable of achieving the desired standards.

In mould assembly, gauges are being used to check the correct position and alignment of individual cores.

Heat treatments near the solidus temperature eliminate interdendritic segregation and homogenize the structure of the casting. This enables the best possible mechanical properties to be achieved.

Nowadays, testing processes are very extensive and costly, both at the production and inspection stages. Constant monitoring of gas content, grain size and modification are now indispensible. Raw and machined castings are inspected using fine focus and image intensifying equipment. Manipulators allow castings to be inspected in various positions directly in front of the X-ray tube. This permits much more reliable evaluation of results. It is often possible to learn more from this type of inspection than from X-ray film. Metallographic tests establish DAS values and allow conclusions to be drawn as to mechanical properties.

In spite of a whole range of new possibilities , casting remains a process which confers form and shape, and of which many aspects defy control. Furthermore, several factors of decisive significance in the foundry are either extremely difficult or impossible to quantify. Binder systems are a good example. Tiny fluctuations in composition or in the type of pre-polymerisation of the resins can lead to decisive changes in quality.

New directions are required

The challenge of the future is to plan and consciously to create the quality of castings. A system of rules must be developed to guarantee the best possible quality in aircraft castings. From today's standpoint, the logical conclusion of this development is the expert system, as it already exists in several other fields of technology.

At present the procedural (mathematical) knowledge available in the foundry is extremely limited. However, it is constantly on the increase.
However,in the case of declarative knowledge, the situation is quite different. Experience, observations, rules and facts are features of special significance in the foundry for maintaining and improving quality levels.

Admittedly, the application of expert systems will be especially difficult for the highly complex castings in use the fields of aeronautics and defence.It should however be regarded as a target for the future.

Using certain basic data, optimum quality should be planned and acquired by systematic effort, even at the earliest stages.
Expert knowledge in the various disciplines must be brought to bear and fully exploited even at the development stage of a casting. Today, it is still widespread practice for only internal working groups to participate in conceiving a casting (design, statics, machining, assembly, internal testing).

At the initial stage, highly specialised knowledge of materials, and in our case, extensive practical foundry experience, are often given only a minimum of consideration. Foundry requirements are only taken into account at the quotation stage, where they lead to modifications, compromises and ambiguous statements concerning quality.

For this reason, consultations should take place between all the parties concerned at as early a stage as possible, in order to make effective planning possible, not only of production, but also of quality.
The essential precondition is thus a common evaluation of the casting component by the various specialist departments inside and outside the foundry, at a very early stage in the conception of the component.

Foundry specialists should, indeed must, draw attention to potential production problems and comment on the desired mechanical and metallurgical requirements right at the start. It is at this stage that the following factors should be settled by mutual consultation:

- the alloy
- the most suitable casting process
- optimum design from the point of view of casting technology
- layout of the pattern and choice of pattern material
- methods and extent of testing, and if possible, procedures of the testing process.

Questions of design, statics, patternmaking and machining can then be effectively dealt with by this group of specialists. Assessment of such factors, as the use of CAD/CAM in producing drawings and patterns, shrinkage, machining allowances, the distribution of stresses in the casting and the final machining of the casting can be discussed and dealt with from various points of view.

Colsultations with foundry engineers enable the most economical casting process to be selected (sand or investment casting).

The perfection of the casting with regard to moulding technology and metallurgical characteristics can be weighed up by the experts and achieved step by step. A data bank for the simulation of solidification in different sections and transitional areas may well have come into being in a few years' time. This would enable reliable statements to be made regarding structure and mechanical and dynamic properties.

On the basis of the information provided by foundry and statics specialists, the testing department can suggest the extent to which the quality of the product may have to be certified and the methods to be used.

If we assemble these experiences, observations and conclusions, and make them accessible for computer processing, an expert system for the foundry could be brought into being in the near future as already visualised by G. Betz and W. Schaefers (1).

With appropriate modifications, this could also be applied to aeronautics castings and have a positive influence on their quality.

A further point which has not yet been mentioned, is that of economic viability. Today, the cost factor is often the very last one to be discussed by technicians in the aeronautics industry, or is simply accepted without further comment.

The production and inspection measures nowadays being demanded mean that the manufacturing costs of aircraft castings have increased significantly.

For this reason, the development of new methods and processes by foundries producing castings for the aeronautics industry are urgently needed. These should allow the required standards of quality to be achieved as economically as possible

New methods, for example, expert systems could help to cut down on unnecessary inspection procedures. On the basis of their own experience, observation and practical rules, individual specialists could draw attention to weak points in fabrication and thus perhaps even simplify testing procedures or apply these in a more rational and effective way. This is the only way in which we in the aeronautics industry will be able to bring the cost factor under control.

Literature

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Metall 64 (1988) No. 5, pages 510 - 512

THIN WALLED CAST HIGH-STRENGTH STRUCTURAL PARTS

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It will be reported about production and reproducibility in series of thin-walled high-strength structural parts out of aluminium and titanium alloys produced to the investment casting process.

Limits referring to dimensions of parts, wall thicknesses and mechanical properties will be shown on choosen examples.

Actions of quality assurance for reproducibility in series are necessary. First of all these include pre-material, melt, casting, ceramic coating, heat treatment.

Also the good compatibility of the material combination titanium and CFA will be considered.

Introduction

Investment castings in light metal alloys aluminium and titanium are widely used in aircraft and aerospace as high strength structural parts in airframe construction and as heat resistant parts in jet engines.

Aluminium alloys are used also within flying instruments as frames, housings for electronical and optical purposes.

The use of investment casting makes it possible to save to a considerable extent processing costs, joining costs (soldering, welding) and material costs.

Lost wax investment casting gives the designer plenty of scope, producing castings with accurate dimensions and excellent surface finish.

The castings are largely ready for assembly - thus saving material and making further fabrication stages unnecessary.

A number of components can be combined in a single casting - costly and difficult joining processes can be avoided.

For the manufacture of investment castings it is particularly important that contact between designer and foundry is made at the earliest possible moment in the development of components, systems or designs in order to optimize carefully the casting shape, to choose the right material and to determine the tolerances.

Development on the investment casting process

For the manufacture of thin-walled large area investment castings a new generation of wax injection machines is needed. By means of a new developed control system in the wax injection nozzle, production of wax patterns are made identical conditions of pressure and temperature. In this way, the shrinkage of the wax is held constant. Thus, wax patterns are made consistently with the tightest of tolerances. Nowadays wax injection machines are designed with a clamping force of 200 t. These permit the manufacture of wax patterns with dimensions of 1500 x 1200 x 400 mm. The handling with such large wax patterns is the real difficulty wher producing the castings. One condition to meet the tight tolerance is to store the wax patterns on special fastening devices and to assemble these to solid clusters. Of course, the prior condition for production of such large parts is to have available the equipments necessary for the total production cycle like dipping tanks with a diameter of 1.5 m, dipping robots with corresponding carrying force, autoclave for dewaxing as well as heat treatment furnaces which can pick-up large castings on devices for heat treatment.

It is absolutely necessary that the rooms have to be air-conditioned and have to show a certain humidity. Only by this there is guaranteed that any deformation of the wax within the pattern does not arise and that drying of ceramics does occur homogeneously.

For the manufacture of aluminium investment castings different casting techniques are used nowadys: open shop casting, vacuum casting, solidification under pressure and manufacture of low pressure investment parts. Which procedure will be used depends on the requirements imposed on the casting in respect of mechanical properties, X-ray quality and the importance of wall thickness ratio.

For production of titanium investment castings future development of moulding system is aimed at developing a system which has little or no reaction with molten titanium. In this way, the occurance of alpha-case, e.g. an oxygen rich diffusion zone, can be avoided instead of having to pickle it off as is done at the moment.

The vacuum arc furnace is primarly used worldwide in the melting and casting of titanium. In addition to the well-known technical and metallurgical advantages of the vacuum arc furnace, one must also add energy saving in comparision with other processes.

The advantage of the low pressure casting process are not only in the casting technique (smooth die filling, good feeding, high output) but also in metallurgical point of view. The melt within the furnace is closed against atmosphere what avoids a too high production of oxygen.

Examples of structural parts in al-alloy

The flap track pick-up for Airbus A 320 was a prime investment casting design (Fig. 1).

The decision to make this mount and load input bracket to the inner carbon fibre flap as an aluminium investment casting was based on the encouraging results of the comparison tests during the development stage. The optimum shape for the component in respect of load path was arrived at, and with it high fatigue strength. In spite of the large dimensions 575 x 250 x 210 mm, the accuracy is high that only fitting holes needed to be drilled and no other machining was needed. Wall thicknesses lay between 2.5 and 40 mm. In comparison with a conventional revetted construction, the investment casting resulted in a saving of about 6 % in weight. Rivetting would mean a multitude of individual parts, while a single investment casting leads to significa.tly lower capacity problems in manufacture and storage.

Fig. 1

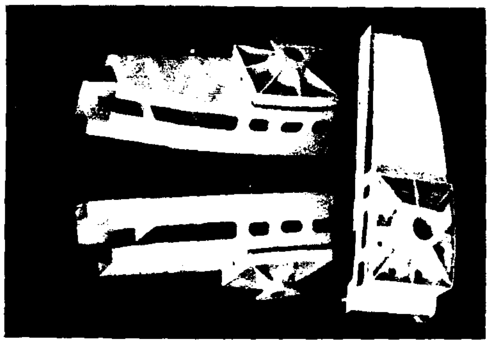

Fig. 1: Flap track pick-up for Airbus A320, alloy: 3.2384.6

The material used is the aerospace material G-AlSi7Mg0,6, equivalent to MIL-C-21180. Guaranteed properties throughout the component are UTS 300 N/mm², Proof Stress 250 N/mm² with more than 5 % elongation. The casting design leeds to a price reduction of 60 % against a conventional sheet design.

Fig. 2:

Fig. 2: Cable guide, alloy: 3.2384.6

During a breakdown of both the electronic and hydraulic systems the pilot can steer mechanically the airplane in an emergency. The "spider" shown in Fig. 2 is an optimal designed investment casting with wall thicknesses of 2 to 15 mm. Guaranteed properties throughout

the component are 310 N/mm² tensile strength, 250 N/mm² proof stress and 5 % elongation.

Fig. 3

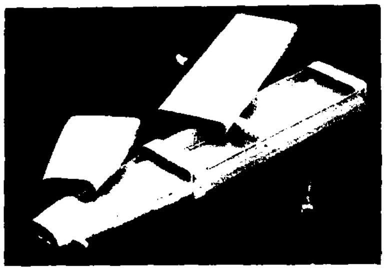

Fig. 3: Electronic housing, alloy: 3.2384.6

Fig. 3 shows an electronic housing with a length of 1 m and wall thickness of 2.2 mm. You can see that the covers are also investment castings which are fixed by means of the cast grooves - which take up the sealing - on the real instrument zone. Within the critical locatings which are used for hanging the electronic part under the aircraft a tensile strength of 320 N/mm² is guaranteed.

Fig. 4

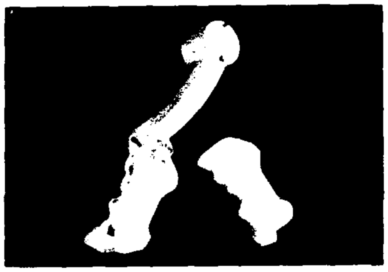

Fig. 4: handle, alloy: 3.2374.6

The handle for the pilot is adjusted to his hand and can fulfill different functions. The casting is with a wall thickness of 1.6 mm extremly thin-walled. The cable duct from the handle to the junction point is made by a water soluble core.

Fig. 5

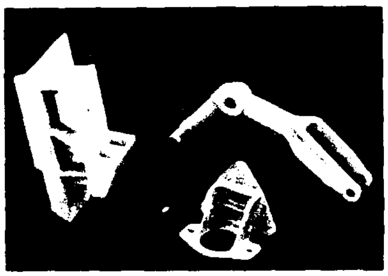

Fig. 5: some different investment castings

The investment castings shown in Fig. 5 are high strength joining elements. The advantage of the castings is the perfect anisotropy of mechanical properties compared with forgings or parts made out of sheet material. There do not exist any priveleged directions of tensile strength and elongation as well as no preferred orientation.

Fig. 6: Cargo door for Airbus A 320

Alloy: 3.2384.6

The Cargo door for Airbus A320 has dimensions 1300 x 1000 x 120 mm, with wall thickness between 1.9 an 15 mm. Throughout the casting UTS of 320 N/mm², Proof Stress of 270 N/mm² and more than 7 % elongation were achieved. The overall weight of the cargo door is 19.4 kg. It is still a developing component. The cargo door is not yet produced within series. At the existing 4 castings a linear tolerance of ± 1 mm over the total length of the component were achieved.

The part which was first designed as a sand casting can be optimized further as investment casting. By means of reduction in wall thickness in certain areas the total weight can be reduced.

Examples of designs out of Titanium alloys

Fig. 7:
Wing spoilers for Airbus A 310

Alloy: G-TiAl6V4

For the mounting of the Airbus wing spoilers (Fig. 7) it was essential to have light weight with complete safety.

The spoiler has been designed to save material and optimise the load paths such that stress peaks do not arise at any position, having a very advantageous effect on the life of the part. The economic advantages are enormous: 96 % of the total machining and assembly costs are saved. Spoiler dimensions are 320 x 400 x 150 mm, the material being Ti6Al4V to ASTM-B 367-C5.

Fig. 8:

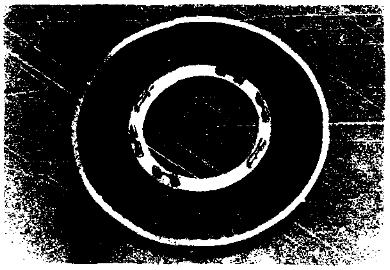

Fig. 8: Stator, alloy: G-TiAl6V4

Up to now, titanium and its alloys have not been used in the form of rotating parts in the aerospace industries. The stator (Fig. 8) has a diameter of 720 mm and contains 64 individual blades, the blade thickness being between 1.5 and 2.5 mm. Total weight is 15 kg, the material Ti6Al4V.

A helicopter rotor head, cast in Ti6Al-4V is shown in Fig. 9.

Fig. 9

Fig. 9: Helicopter rotor head, alloy: G-TiAl6V4

Fig. 10 shows the Spacelab structure, in which the nodular fasteners and side pieces (trunnion adaptor) are made as titanium investment castings.

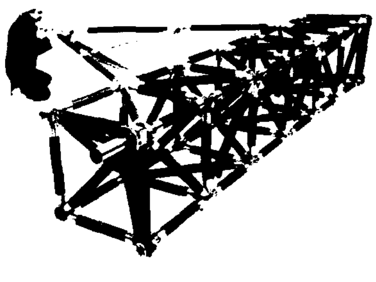

Fig. 10: Spacelab structure - nodular fasteners and side pieces - titanium investment casting - alloy: G-TiAl6V4

These hold the carbon fibre reinforced tube bundles and, in this way, build up the strong and lightweight structure.

Future development in aluminium investment castings

Fig. 11:

ALUMINIUM INVESTMENT CASTING

Criterion	grade I	grade II ~ 1985	grade III ~ 1995	Remarks
max. component sizes (mm)	500x500x850	500x800x1500	800x1000x2000	
min. wall/rib/bottom thickness (mm) with max. component sizes	1,6	1,5	1,4	
wall thickniss steps proportion/step area	1 : 2,5	1 : 5	1 : 8	
wall/rib/bottom thicknesses tolerance (mm)	± 0,15	± 0,15	± 0,15	
alloy mechanical properties with RT Rm Rp0,2 A5 critical areas: grade B	A 357 K 01 350 420 280 350 3 3-5	 470 400 5	 530 450 6	Casting factor = 1.0

Fig. 11: Technoeconomic analysis of VFW 1982

Fig. 11 shows the requirements which aluminium investment castings will have to meet in future. This illustration is 6 years old and was also drawn up by Vereinigte Flugtechnischen Werken as a technoeconomic analysis.

The aerospace industry will be looking for the following requirements from the future generation of aluminium investment castings:

1. Thin walls
2. Maximum overall dimensions
3. High mechanical properties as well as high elongation.

If procedure of aluminium investment casting succeed in being able to offer designers and stressmen a assured consistency in static mechanical properties, it will be possible, to reduce casting factor to 1.0. Statistical evaluation of properties achieved and defects found will be particularly important in this respect.

Development of high strength aluminium investment casting alloys is in the early stages. On the basis of the alloy A 357 or G-AlSi7Mg 0,7 and K01, used up to now, the future requirements of the aircraft industry cannot be met. As far as aluminium lithium alloys are concerned, the literature todate shows conflicting data. With aluminium lithium alloys, the elastic modulus and crack length can be increased and the density reduced. An increase in strength together with increased ductility is, to be sure, not to be expected.

There are, as yet, no data on the introduction of short fibres into aluminium investment castings. The insertion of long, wound fibres in aluminium investment castings with wall thicknesses of 1.5 or 2 mm appears unlikely, since, with such wall thicknesses, the mould filling capability is no longer realisable.

One of the future application areas for titanium lies in the combination with fibre reinforced carbon fibre-compound material.

ADVANCES IN THE TECHNOLOGY OF TITANIUM CASTINGS

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Summary

This paper describes the techniques used for making titanium casting and how current mould making methods can produce pieces with good dimensional tolerances and surface finish. Both rammed sand and lost wax investment methods can be used for mould making, the choice depending on piece complexity, weight, required surface finish and economic considerations. Hot Isostatic pressing is normally applied to castings for aerospace and results are presented showing the beneficial effect of this process in terms of reduction of internal porosity. The effect of HIP on mechanical properties is also presented.

(1) Introduction

There are several economic and technical arguments for using titanium alloys in aerospace applications. The combination of strength, stiffness, density and corrosion resistance give it a significant advantage over other alloy bases in many engineering applications. The titanium alloys are, however, relatively difficult to machine and this makes the use of castings very attractive.

(2) Casting Techniques

There are three major problems in the production of titanium castings.

(a) High melting point of the alloys, generally above 1700°C.
(b) Low fluidity of the metal at pouring temperatures.
(c) High reactivity with almost every gas, liquid or solid at temperatures above 500°C.

The usual method of melting titanium for the casting process is to use consumable electrode arc melting in a vacuum. The melting crucible is a double walled copper container with water cooling, which causes a solid skull of titanium to be formed on the inner surface. This skull and the absence of atmosphere protects the molten metal from contamination.

Once the titanium electrode has been consumed there is no more heat input to the system and the metal must be poured into the moulds as quickly as possible before further solidification in the crucible occurs. The batch weight at SETTAS S.A. is 1 tonne of metal and a centrifugal casting arrangement is used to move this metal into the moulds. The melting and casting equipment is shown diagramatically in Figure 1. The mould assembly has a diameter of up to 3 metres and, when rotating, generates a centrifugal force of up to 60G at the periphery. This force ensures fast movement of the metals into the moulds and also provides extra pressure for feeding during solidification.

(3) Moulding Methods

The two principle methods for making moulds are:

(a) Ceramic shells made by the lost wax process - investment casting.

(b) Precision sand and graphite - rammed sand.

The choice between the two depends on the complexity of the cast piece, the required dimensional tolerances and surface finish, and economic considerations.

The dimensional tolerances which are obtainable from the two processes are given in Table 1. The investment casting technique can be used to make complex shapes with a surface finish of 3μ. However the cost of the wax pattern dies is high and therefore this method is better suited to long runs. It is also amenable to the use of robotics in the shell making process. Typical examples of castings made by the lost wax process are shown in Figure 2.

The precision sand method is generally used for simpler shapes and the surface finish is slightly inferior to that obtained on investment castings, typically about 6μ. However the tooling used to shape the sand/graphite mixture is relatively inexpensive and the technique can be used to make large pieces. Typical examples of castings made by the precision sand method are shown in Figure 3. This technique is a standard production route for aerospace parts and, with the flexibility offered, it is a preferred route during the development phase before the design is fixed.

Comparison of mechanical properties obtained from castings made by the two moulding methods are given in Table 2. Both routes give material which meets the relevant ASTM specification. The sand casting has slightly higher tensile properties and ductility and this may be related to the fact that this route produces a smaller grain size than that obtained in equivalent investment castings. For equivalent sections the investment casting had an ASTM grain size of <00 whereas the sand casting had grains in the size range ½ - 0.

(4) Casting Quality

There are several other factors which have to be considered when aiming for a sound titanium casting. The first is shrinkage control to which is applied the normal rules calculating the size and position of risers and in-gates. In the precision sand process there is the possibility of using various moulding mixtures to give a progressive chilling effect but this is not so easy with investment casting shells. There is an extra complication imposed by the centrifugal casting process. This gives an added compressive force in the radial direction of the chamber. This also leads on to the second consideration which is mould distortion. All the usual precautions need to be taken during mould making, dewaxing, drying and firing to control and monitor mould distortion and shrinkage. In addition, because of the extra hydrostatic and gravity forces during casting, particular care has to be taken in mounting and supporting the moulds in the chamber. There is also a need to ensure that the mould assembly is balanced in relation to the axis of rotation, both before, during and after filling, otherwise mechanical instability will result.

The third consideration in casting quality relates to surface contamination. Although titanium is cast under vacuum and in a mould made of an appropriate non-reactive material, it is quite difficult to avoid any contamination of the casting surface by oxygen, carbonaceous material or first coat oxides picked up by the molten metal from the mould surface at the time of pouring. The resulting layer of contamination known as alpha-case shown in Figure 4 is very hard and can range in thickness from 0.3mm down to zero. The alpha-case, because it is hard and can easily initiate surface cracks, has to be removed and this is usually done by chemical milling in mixed acids. Obviously to achieve good dimensional tolerances and good surface finish in the casting, the alpha-case thickness and its removal need to be controlled and monitored. Removal of the alpha case has the added benefit that it generally further improves the surface finish.

(5) Hot Isostatic Pressing

The final factor to be considered in relation to quality is internal microporosity which is inevitably present in any casting. Although this is minimised by appropriate foundry engineering and the imposition of centrifugal force there is still a need, particularly in pieces for aerospace, to take further steps to ensure the absence of internal cavities. This is done by the application of hot isostatic pressing (HIP). This is very effective in producing full densification of titanium and its alloys, but it is necessary to monitor distortion which may result from the process.

Trials have been done at SETTAS S.A. in order to define the effect of HIP on structure and properties. The standard cycle is :

HIP at temperature : 900°C
pressure : 100MPa
time : 2 hours

followed by a vacuum heat treatment of 2 hours at 750°C.

The effect on mechanical properties is given in Table 3 and this indicates that HIP increases the ductility of the metal. With regard to the effect on porosity level, this is shown in the micrograph in Figure 5 and also in the quantitative metallography histogram in Figure 6. For this latter technique six micrographs from each sample, at a magnification of x50, were analysed in order to record a statistically significant number of pores. The results are also tabulated in Table 5.

(6) Conclusions

Casting techniques for titanium alloys are reliable and predictable. Both rammed sand and lost wax investment methods can be used for making moulds which produce castings with good tolerances and surface finish. Both methods give castings with mechanical properties which meet the relevant ASTM specifications. The internal quality of the castings can be further enhanced by the application of HIP which either completely eliminates internal cavities or significantly reduced their size.

Acknowledgements

The authors wish to thank Inco Engineered Products Ltd. for permission to publish this paper.

TABLE 1
COMPARISON OF MOULDING METHODS

Method	Pattern	Moulding Material	Surface Finish (μm)	Diameter Tolerance (mm)	Thickness Tolerance (mm)
Precision Sand	Wood, Resin	Special Sand	6	750 +/-2	2.5 +/-0.6
Lost Wax	Metal + Wax	Ceramic	3	750 +/-1	2.5 +/-0.3

TABLE 2
COMPARISON SANDCASTING/LOST WAX CASTING

TITANIUM: Ti 6Al-4V - ASTM B-367-83 Grade C5

% O_2	Treatment	Casting	0.2% Elastic Limit (MPa)	U.T.S.	Elongation %
0.19	HIP + Heat Treatment	Sand	870	980	12.5
0.19	HIP + Heat Treatment	Lost Wax	840	950	9
ASTM B-367-83 Grade C5			825 (min)	875 (min)	6 (min)

TABLE 3
COMPARISON OF AS CAST/HIP + HEAT TREATMENT OF SAND CAST

% O_2	Treatment	0.2% Elastic Limit (MPa)	U.T.S.	Elongation %
0.22	As Cast	890	1065	8.5
0.22	HIP + Standard Heat Treatment	890	1015	10.5

TABLE 4
POROSITY MEASUREMENT

As Cast			After HIP	
Thickness mm	Surface μm^2	Length μm	Surface μm^2	Length μm
25	4519	62.87	152	16.00

The results show the amount of porosity, measured both in terms of the surface area and the length, using quantitative metallography techniques.

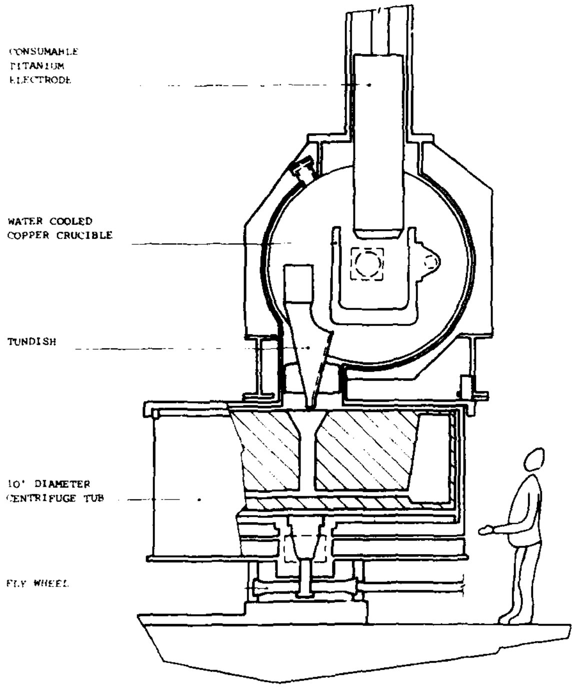


FIGURE 1 Diagram of centrifugal casting furnace used for making titanium castings

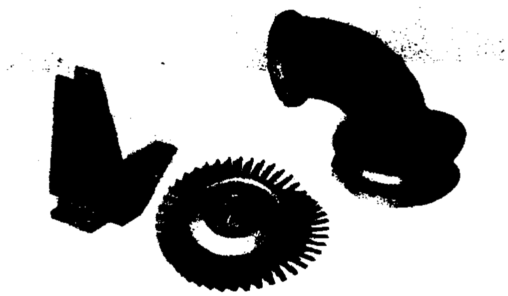


FIGURE 2 Typical titanium castings made using the lost wax investment process

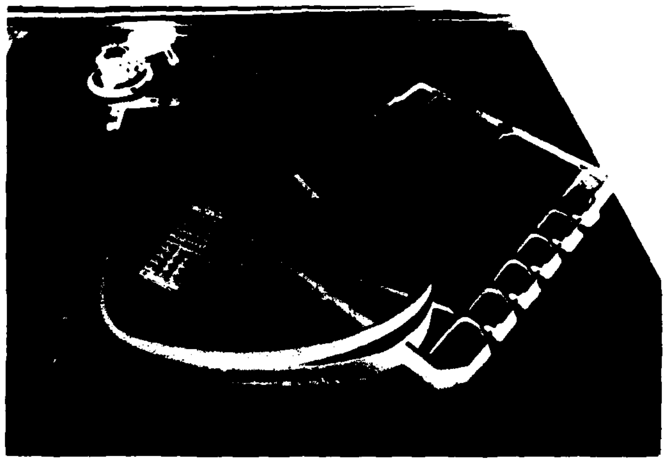
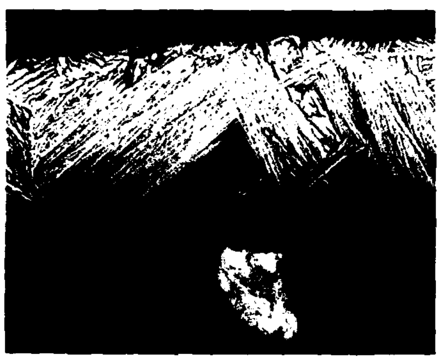
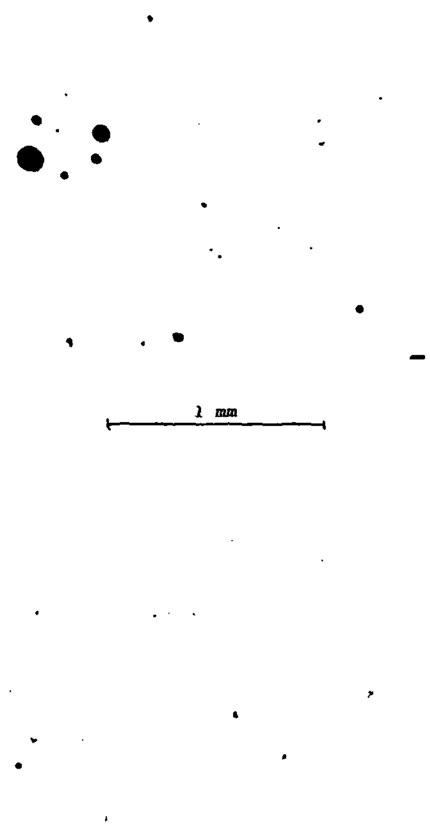


FIGURE 3 Titanium castings made using sand/graphite moulding techniques



x100

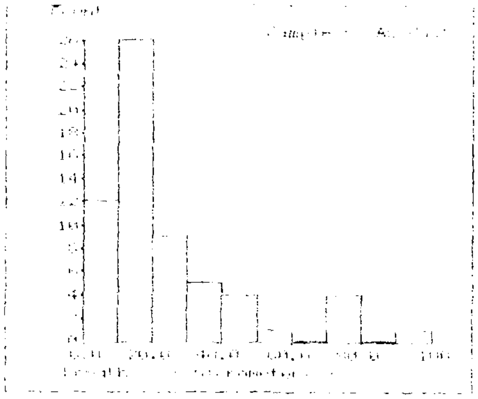
FIGURE 4 Alpha case on surface of titanium casting



AS
CAST

CAST
+
HIP

FIGURE 5   Porosity in cast titanium (top) and after
Hot Isostatic Pressing (lower)



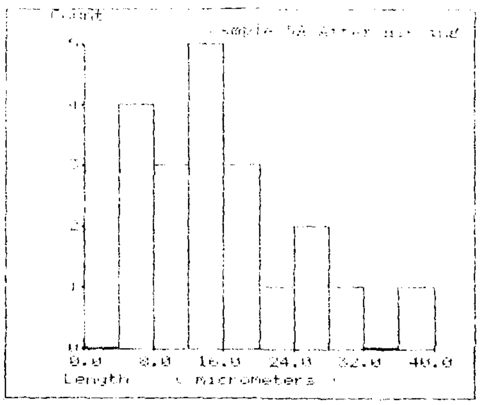


FIGURE 6 **Quantitative metallographic measurement of pore size and number in as-cast (top) and cast + HIP (bottom) titanium.**

[Note different x- and y-axis values]

MICROSTRUCTURE MORPHOLOGY

AND

QUALITY OF AL-SI CASTINGS

by

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SUMMARY

The effect of strontium addition on the microstructure has been investigated for Al-Si hypo-eutectic casting alloys. It is shown that strontium modification changes the eutectic morphology from acicular or lamellar to fibrous. The study was carried out on samples cast in sand and in investment shell molds.

The correlation between microstructure and mechanical properties has been established. It has been demonstrated that tensile strength and elongation, and impact strength are greatly improved by the Al-Si eutectic modification.

Finally, technicques such as thermal analysis and electrical resistivity will be presented and their application as a quality control technique discussed.

INTRODUCTION

In recent years developments in metal processing and molding has opened new areas of application in the aerospace industry for Al-Si alloys. High quality parts are obtained by sand molding or investment casting.

Al-Si-Mg alloys such as A356.0 offer a good compromise between high mechanical characterics and good castability. Mechanical properties are influenced by four main factors: porosity, dendritic arm spacing (DAS), grain size, and Al-Si eutectic structure. An increase in cooling rate has a beneficial influence on each of these factors. But at a given cooling rate the Al-Si eutectic structure is positively affected by the addition of strontium (1).

The influence of strontium on the microstructure of the Al-Si eutectic has been studied extensively. It has been shown that the eutectic modification of Al-Si hypoeutectic alloys improves the mechanical properties significantly (2).

The present study was carried out on samples cast in sand and investment shell molds. Results are presented showing the correlation between microstructure and mechanical properties.

EXPERIMENTAL

All the experiments in this work were conducted on A356.0 alloys having the composition given in Table 1.

Ingots of A356.0 alloys were remelted in a 10kg SiC crucible fired in a gas furnace. Strontium was added in the form of a 90%Sr-10%Al alloy or pure metal. All additions were made at temperatures between 730°C and 750°C.

Sand Castings

All melts were degassing with a nitrogen freon 12 mixture (95% N_2 - 5% C Cl_2 F_2). The degassing agent was bubbled into the melt at a rate of 1.5 litres per minute.

After degassing the melt was poured between 715 to 725°C into sand molds at room temperature to produce separately cast test bars according to Canadian Standard Association specification HA1.

In the case of sand castings, the following heat treatment schedule was applied to the A356.0 alloy type;

- solution treatment at 540±5°C for 72 hours
- water quenching to 25°C
- natural aging for 48 hours at room temperature
- precipitation hardening at 155±5°C for 8 hours

Investment Casting

After strontium addition, the melt was degassed with pure argon. The inert gas was bubbled into the melt at a rate close to 1.5 litres per minute. After a 20 minutes degassing period, the metal was poured in ceramic molds which were preheated between 815 to 925°C. Blocks of metal having a dimension 3cmx3cmx8cm were obtained and two unnotched Charpy samples were machined from each cast sample.

The cast samples were heat treated according to the following cycle:

- solution treatment at 538°C for 14 hours
- water quenching to 75°C
- precipitation hardening at 155°C for 4 hours

Thermal Analysis

The system used for thermal analysis is described in detail by Argyropoulos and al.(3). The analog signal, obtained with a type K thermocouple, is converted to a digital signal by a converter which can be located remote from the microcomputer system. The data of each thermal analysis are stored on a floppy disk for further processing.

Thermal analysis samples were poured into a cylindrical cup made of thin (1mm) iron sheet having a diameter of 60mm and height of 50mm.

The simple thermal analysis involves the plotting of temperature versus time during a phase change and is the most widely used method to study a transformation during cooling or heating. The following characteristics are determined for each cooling curve:

- liquidus nucleation temperature: T_N(°C)
- liquidus temperature: T_L(°C)
- $\Delta T2=T_L-T_N$
- eutectic nucleation temperature: T (°C)
- eutectic growth temperature: T_E(°C)
- $\Delta T1=T_E-T_C$(°C)
- $\Delta T=T_E-T_{E'}$(°C)

where $T_{E'}$ = 575°C for an A356.0 alloy

Electrical Conductivity

Before heat treatment conductivity measurements were carried out at room temperature on a cut section of the investment cast block. A K.J. Law model M4900B electrical conductivitymetre was used. This device is temperature compensated and measures the conductivity by an Eddy Current technique as a percentage of the International Annealed Copper Standard (pct. IACS).

RESULTS

Sand Casting

Mechanical Properties

The major mechnical properties after heat treatment, i.e. tensile strength (UTS) and elongation (E) are shown in Figure 1. Tensile strength of an A356.0 alloy is relatively unaffected by the microstructure modification. At a strontium level between 0.005% and 0.015%, the elongation is increased by approximately 50%.

The tensile strength and elongation have been combined in the form of a quality indes (4), Q, which for A356.0 alloys is defined as:

$$Q = \text{Tensile Strength} + 150 \log (\%E)$$

The variation of the quality index with strontium is shown in Figure 2 for test bars solidifying at a rate of 1.5°C s^{-1}. The increase in the value of Q with strontium is due to changes in the elongation rather than the tensile strength.

Figures 1 and 2 show that the mechanical properties are very sensitive for the strontium level and that it is possible to both undermodify and to overmodify the alloy. From the slopes of the curves in Figure 2, it is clear the undermodification is slightly more critical than overmodification.

Metallography

The effect of strontium addition on the as-cast microstructure is shown in Figure 3. The unmodified structure (Figure 3a) contain coarse acicular silicon. Figure 3b shows well modified structures of fine fibrous eutectic silicon, and this structure would be typical of that required to obtain the best mechanical properties.

Investment Casting

Mechanical Properties

Impact strength measurements were performed on heat treated unnotched Charpy samples. Table 2 shows the effect of strontium addition and structure modification on impact strength. Before modification (0%Sr), the impact strength is only $2.75 Jcm^{-2}$. After addition of 1g of a 90%Sr-10%Al alloy, the strontium content of the melt is increased to 0.009%, and consequently the impact strength is improved to $10.10 Jcm^{-2}$. Further addition of strontium to a 0.017% level does not improve significantly the impact strength which reaches $10.65 Jcm^{-2}$.

After a second degassing period with a N_2-5% freon mixture resulting in a strontium removal to a 0% level, the impact strength is reduced to $4.10 Jcm^{-2}$ which is close to the initial level of $2.75 Jcm^{-2}$. A subsequent addition of 0.003% strontium increases the impact strength to $7.50 Jcm^{-2}$.

Metallography

Figure 4 shows the effect of strontium modification on the as-cast structure of the A356.0 alloy cast in an investment sheil mold. At 0% strontium, the unmodified structure exhibits a coarse acicular eutectic silicon (Figure 4a). A 0.009% strontium level is adequate to change the acicular structure to a finely dispersed Al-Si eutectic (Figure 4b). The strontium removal to 0% by degassing with a N_2-5% freon mixture results in an acicular silicon morphology. After addition of 0.003% strontium, the eutectic structure becomes only lamellar (Figure 4c) and this strontium level is insufficient to obtain an optimal fibrous silicon morphology at a freezing rate of $0.15°Cs^{-1}$.

Heat treatment acts to change the cast structure with the exact change depending on wether or not the alloy was modified (Figure 5). With nonmodified structures the acicular silicon subsists and is only made less angular (Figure 5a). The fine silicon particles of the cast modified structure undergo some coalescence on heat treatment but nevertheless remain finer than the nonmodified structure. The undermodified (0.003%Sr) exhibits a mixture of fine particles and rounded lamellae (Figure 5c).

Thermal Analysis

The cooling curves corresponding to the eutectic transformation of the A356.0 alloy were analyzed at different strontium levels. Table 3 shows the correlation between strontium modification and thermal analysis characteristics. When the strontium level is increased from 0% to 0.009%, the eutectic temperature decreases from 575.4°C to 569.1°C resulting in a ΔT decrease of 5.5°C. The corresponding value of $\Delta T1$ increases from 0°C to 3.4°C. A higher strontium level (0.017%) does not affect significantly the thermal analysis characteristics. After strontium removal to 0%, the eutectic temperature increases to 576.0°C and $\Delta T1$ = 0C. The addition of 0.003% strontium decreases ΔT only from +1.0°C to -3.3°C and results in an increase of $\Delta T1$ from 0°C to 4.0°C.

Electrical Conductivity

Table 4 shows the variation of electrical conductivity with strontium modification of the as-cast A356.0 alloys. The increase of the strontium level from 0% to 0.009% results in an electrical conductivity increase from 33.1% IACS to 35.2% IACS. A further strontium increase to 0.017% has not a substantial effect on the electrical conductivity. A subsequent strontium removal to 0% results in an electrical conductivity decrease to 32.5% IACS. A small addition of strontium (0.003%) brings the electrical conductivity up to 34.2% IACS. This intermediary level is comprised between 33.1% IACS and 35.5% IACS values corresponding respectively to an unmodified (0%Sr) and fully modified (0.017%Sr) A356.0 alloy.

DISCUSSION

Sand Casting

Strontium is an excellent modifier for Al-Si-Mg casting alloys. The favorable action of strontium on the microstructure is illustrated in Figure 3b, which shows an A356.0 alloy in the as-cast structure and treated with 0.010% strontium. The modified alloy is characterized by solid solution dentrites and by a very fine eutectic analogous to that obtained by sodium modification (5).

The mechanical properties expressed through the quality index increase from 400 MPa for nonmodified alloys to 450 MPa at the optimum strontium level. At a cooling rate of $1.5°Cs^{-1}$, it represents an increase of 12.5%. At lower cooling rates, the quality index is even more sensitive to the degree of modification (6).

Heat treated strontium modified alloys have mechanical property values largely superior to typical properties (7) as indicated in Table 5. Property values quoted from the present work in Table 5 are those corresponding to the optimum strontium level (0.005% to 0.15%).

The increase in the quality index, Q, is due to increase in the elongation of strontium treated alloys for up to 12%.

In addition, the mechanical properties obtained with strontium are better than those reported for sand cast sodium or antimony modified A356.0 alloy shown in Table 6.

Investment Casting

Strontium is a very efficient modifier of A356.0 alloys cast in investment shell mold evendough the freezing rate of the metal is as low as 0.15°Cs^{-1}. The change of microstructure morphology from acicular (0%Sr) to fibrous (0.009%Sr) is accompanied by a dramatic increase in impact strength increase from 2.75Jcm^{-2} to 7.4Jcm^{-2}. The loss of modification reduces the impact strength to a 4.1Jcm^{-2} value which is close to the original value of 2.75Jcm^{-2}. An insufficient strontium level (0.003%) results only in a lamellar eutectic form and in an impact strength value of only 7.5Jcm^{-2} which is significantly below the impact strength (10.10Jcm^{-2}) of a fully modified struture. Impact strength measurements obtained from A356.0 and 413.0 alloys cast in a permanent mold have also shown dramatic improvements after eutectic modification with strontium (10).

Both thermal analysis and electrical conductivity are good techniques to follow nondestructively the microstructure modification resulting from a strontium addition to A356.0 melts. The eutectic form changes from acicular (0%Sr) to fibrous (0.017%Sr) while the thermal analysis characteristic, ΔT, decreases from +0.4°C to -5.6°C. A lamellar structure (0.003%Sr) is characterized by a T value of -3.3°C which is substantially higher than ΔT = -5.9°C corresponding to a fibrous eutectic silicon.

Electrical conductivity increases by approximately 10% when the microstructure changes from acicular (0%Sr) to fibrous (0.017%Sr). A lamellar silicon (0.003%) results only in a 5% increase of the electrical conductivity.

There exists also a good correlation between impact strength and electrical conductivity. Figure 6 shows the variation of both electrical conductivity and impact strength with the strontium content. The change from an acicular eutectic (0%) to a lamellar structure (0.003%) increases the electrical conductivity from an average of 32.8% IACS to 34.2% IACS and the impact strength from an average of 3.5Jcm^{-2} to 7.5Jcm^{-2}. At an optimum strontium level (0.009%) both electrical conductivity and impact strength reach respectively a plateau situated at 35.5% IACS and 10.65Jcm^{-2}.

CONCLUSIONS

The following main conclusions can be drawn from this work:

1. Elongation and impact strength of respectively sand cast and investment cast A356.0 alloys are positively affected by the modification of the Al-Si eutectic morphology.

2. There is an optimum strontium level to achieve the best mechanical properties. The level for both sand and investment cast A356.0 alloys lies between 0.010% and 0.015%.

3. Thermal analysis and electrical conductivity are non-destructive and quantitative techniques capable of controlling the quality of the melt.

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Table 1. Composition of A356.0 Alloys

Element (wt%)	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Al
Sand Casting	7.0	0.10	0.004	0.003	0.33	0.008	0.01	0.14	Bal.
Investment Casting	7.3	0.15	0.01	0.02	0.37	0.001	0.01	0.10	Bal.

Table 2. Impact Strength of A356.0 Alloy

Sr (%)	Impact Strength ft.lb.	J/cm^{-2}
0	2.0	2.75
0.009	7.4	10.10
0.017	7.8	10.65
0	3.0	4.10
0.003	5.5	7.50

Table 3. Thermal Analysis Characteristics of A356.0 Alloys

Sr (%)	Eutectic Nucleation Temperature T_C(C)	Eutectic Growth Temperature T_E(C)	$\Delta T1 = T_E - T_C$ (C)	$\Delta T = T_E - 575$ (C)
0	575.4	575.4	0	+0.4
0.009	565.7	569.1	3.4	-5.9
0.017	565.9	569.4	3.5	-5.6
0	576.0	576.0	0	+1.0
0.003	567.7	571.7	4.0	-3.3

Table 4. Electrical Conductivity of As-Cast A356.0 Alloys

Sr (%)	Electrical Conductivity (% IACS)
0	33.1
0.009	35.2
0.017	35.5
0	32.5
0.003	34.2

Table 5. Comparison of Strontium Modified Alloys with Typical Properties

	UTS (MPa)	YS (MPa)	E (%)	Q (MPa)
Present work	285	208	12	447
Sand cast. T6(7)	230	165	3.5	312

Table 6. Comparison of strontium Modified A356.0 Alloy to Sodium and Antimony Modified Alloy

Modifying Agent	UTS (MPa)	E (%)	Q (MPa)
Strontium	290	12.7	455
Sodium (8)	269	6.5	390
Antimony (9)	270	6.0	386

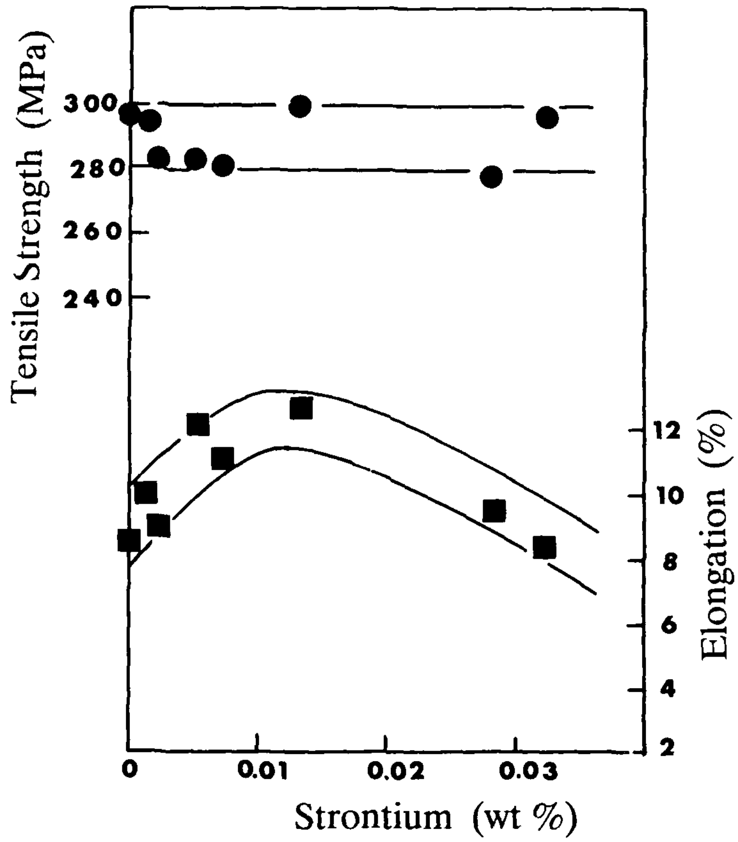


Figure 1. Variation of tensile strength and elongation with strontium content. A356.0 alloys cast in sand mold.

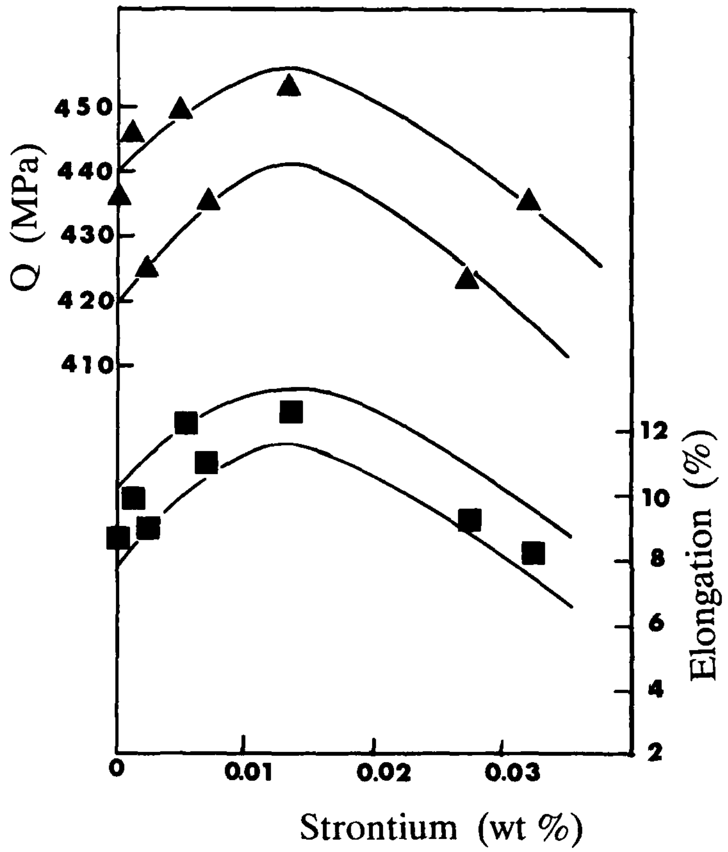
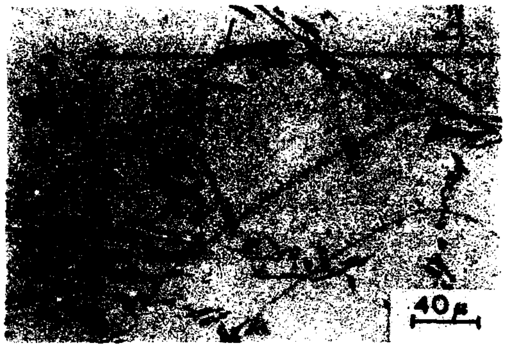


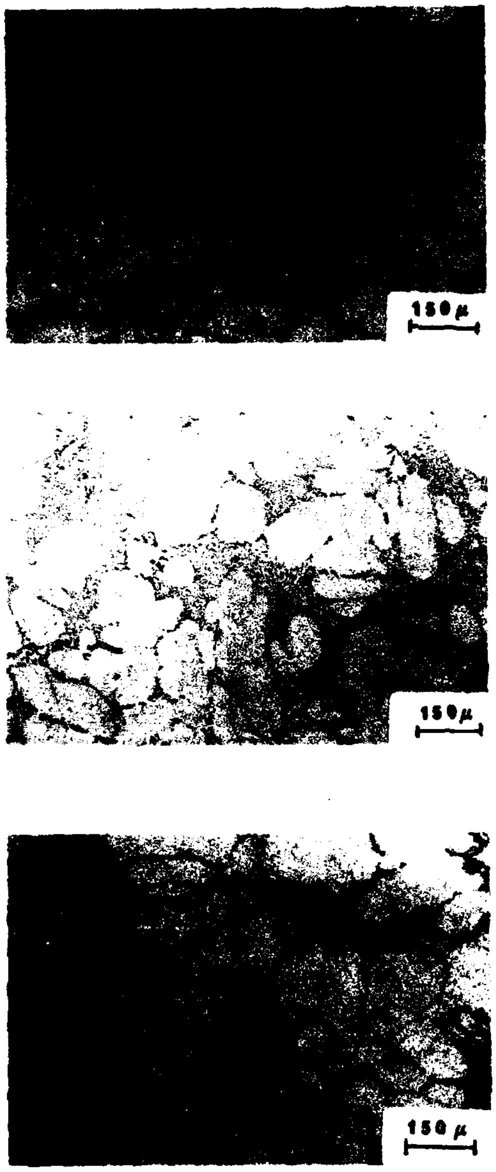
Figure 2. Variation of quality index and elongation with strontium content. A356.0 cast in sand mold.



3a: 0%Sr

3b: 0.01%Sr

Figure 3. Microstructure of as-cast A356.0 alloy cast in sand mold.

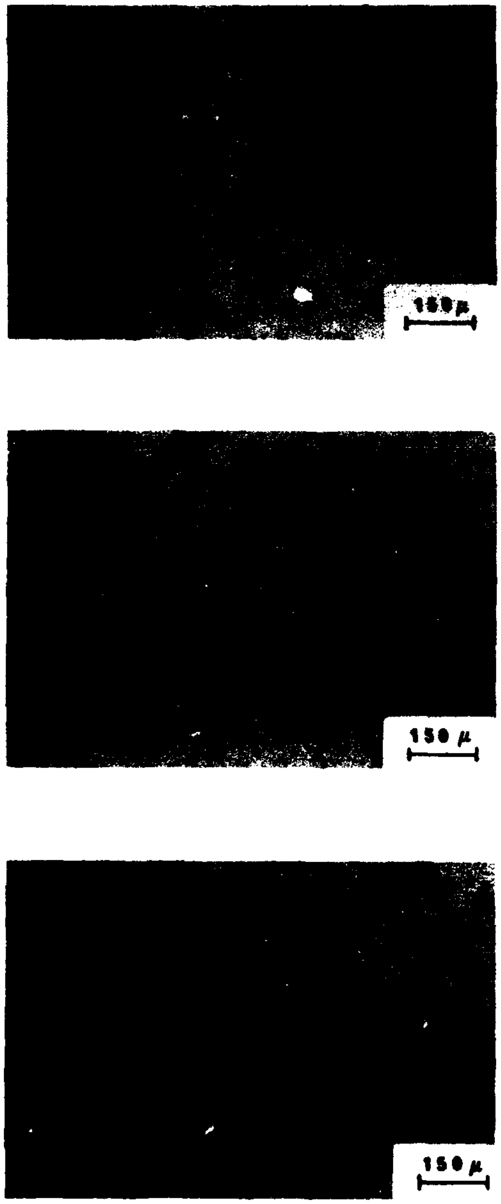


4a: 0%Sr

4b: 0.009%Sr

4c: 0.003%Sr

Figure 4. Microstructures of as-cast A356.0 alloy cast in an investment shell mold.



5a: 0%Sr

5b: 0.009%Sr

5c: 0.003%Sr

Figure 5. Microstructures of heat treated A356.0 alloy cast in an investment shell mold.

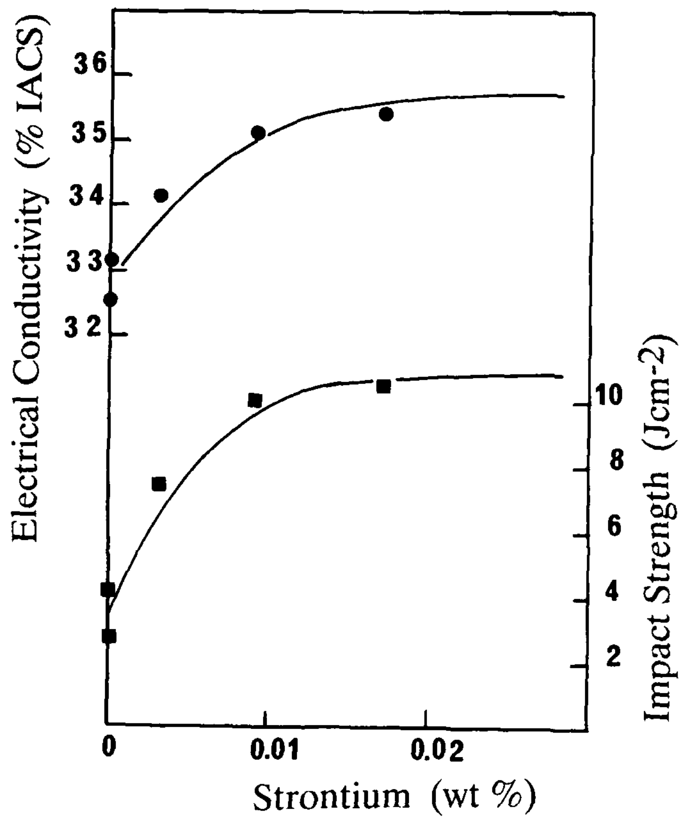


Figure 6. Correlation between electrical conductivity and impact strength at different strontium levels for an A356.0 alloy cast in investment shell mold.

The Improved Corrosion Resistance of Ultra High Purity Magnesium Alloy Castings

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Because of their high strength to weight ratio, good stiffness and excellent damping capacity, magnesium alloys offer significant design opportunities for aircraft manufacturers. In spite of these potential benefits, the application of magnesium castings in modern day aircraft is extremely limited.

The widespread use of magnesium castings in aircraft has been limited by two major concerns;

- flammability
- corrosion

The widespread belief that magnesium is a fire hazard is clearly a myth. Combustibility tests have repeatedly confirmed that magnesium will not sustain a fire unless the entire metal component is heated to in excess of about 500°C. If ignited, the product of combustion is nontoxic magnesium oxide (MgO).

By comparison, many synthetic materials and plastics used to lighten the weight of modern aircraft will support combustion at relatively low temperatures. Highly poisonous emissions from these materials during in-flight cabin fires are a serious concern and have been linked to several passenger deaths. These toxic side effects may be even far more reaching as it has now been reported that workers clearing the site of a recent aircraft crash at Gander are developing long term and persistent health problems which are being attributed to inhalation of toxic fumes emitted from smoldering wreckage. Clearly, these are much more serious and real concerns for aircraft designers.

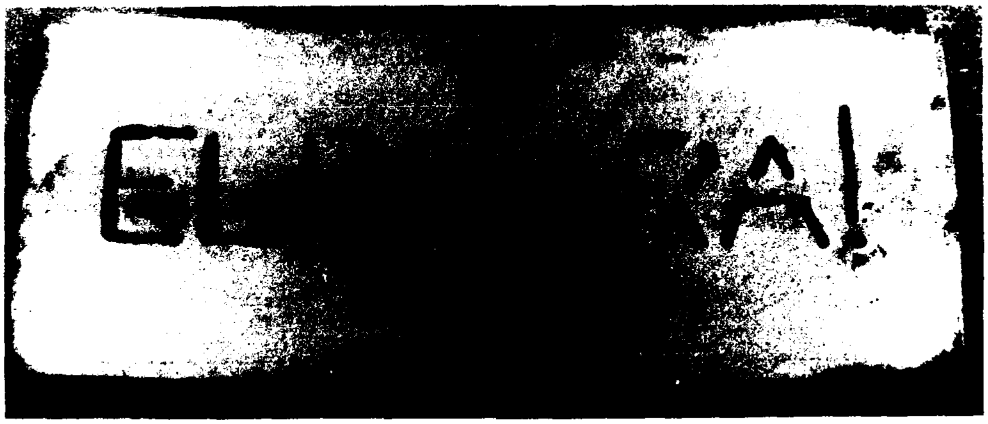

Figure 1: Magnesium Sheet Inscribed With a Welding Torch Without Argon Shrouding. MAGNESIUM WILL NOT BURN UNLESS THE ENTIRE SPECIMEN EXCEEDS ABOUT 500°C (12).

Being the most anodic of all structural metals, magnesium alloys are inherently corrosion prone. Magnesium producers are fully cognizant of the serious nature of the corrosion problems that have historically plagued the metal and, as such, improved corrosion resistance has been the focus of considerable research. As a result of these efforts, the corrosion performance of magnesium alloys has been significantly improved in recent years;

- by establishing good design practices to eliminate sources of galvanic corrosion and moisture traps (1)
- by developing excellent protective coatings and finishing practices (1,2,3)
- by adopting fluxless melting practices to eliminate highly corrosion prone flux inclusions (4,5)
- by developing higher purity alloys with reduced levels of heavy metal impurities (6,7,8,9,10)

This paper reports on the significant and still further improvement in the corrosion resistance of magnesium alloy castings attained by simultaneously reducing the iron, nickel and copper impurities to ultra low levels (less than 15, 10 and 10 ppm, respectively). These ultra-high purity magnesium castings provide exceptionally high and consistent corrosion resistance as required for many critical or value added components where corrosion is a prime concern.

THE EFFECTS OF HEAVY METAL IMPURITIES ON CORROSION: STATE-OF-THE-ART:

Although the detrimental effects of heavy metal impurities on the corrosion resistance of magnesium alloys have been known for many years (11, 12), only recently have the benefits of higher purity alloys been fully appreciated (6,7,8,9,10).

Recent studies using the ASTM standard B117 salt spray corrosion test on the widely used AZ91 magnesium casting alloy (nominally 9% Al, 1% Zn) have shown that the resistance to salt spray is dramatically improved by reducing trace amounts of nickel and copper as well as lowering the iron-to-manganese ratio in the casting.

As indicated in Figure 2, the corrosion rate increases exponentially with increasing impurity levels for both die and gravity cast AZ91 alloys. The somewhat higher corrosion rates associated with gravity castings have been attributed to their larger grain size compared to die cast components. Surface treatments such as sanding or sand blasting combined with acid etching to remove trace amounts of residual iron and T5 or T6 tempering have also been reported to further lower the corrosion rate of gravity cast AZ91 (9, 10).

From the relationships shown in Figure 2, the magnesium industry has established impurity tolerance or threshold limits beyond which the corrosion rate of AZ91 increases rapidly. These tolerance limits have been incorporated into the specifications for high purity AZ91 alloys for die and gravity casting applications (Table I). Provided heavy metal impurities do not exceed these specification limits, the corrosion resistance of die cast AZ91D high purity alloy has been reported to be equivalent or superior to die cast 380 aluminum and cold rolled steel (9,10).

Table I: Chemical Specifications for Current Commercial High Purity AZ91 Alloys

Alloy	Designation	Specification Max %			Min %
		Fe	Ni	Cu	Mn
Current Alloys					
AZ91D	ASTM High Purity; Die Cast	0.004	0.001	0.015	0.17
AZ91E	ASTM High Purity; Gravity Cast	0.005	0.0010	0.015	0.17
AZ91X *	TIMMINCO High Purity	0.004	0.001	0.003	0.17

* The acronym "X" is not an assigned ASTM listing and refers to Timminco Metals generic designation for high purity.

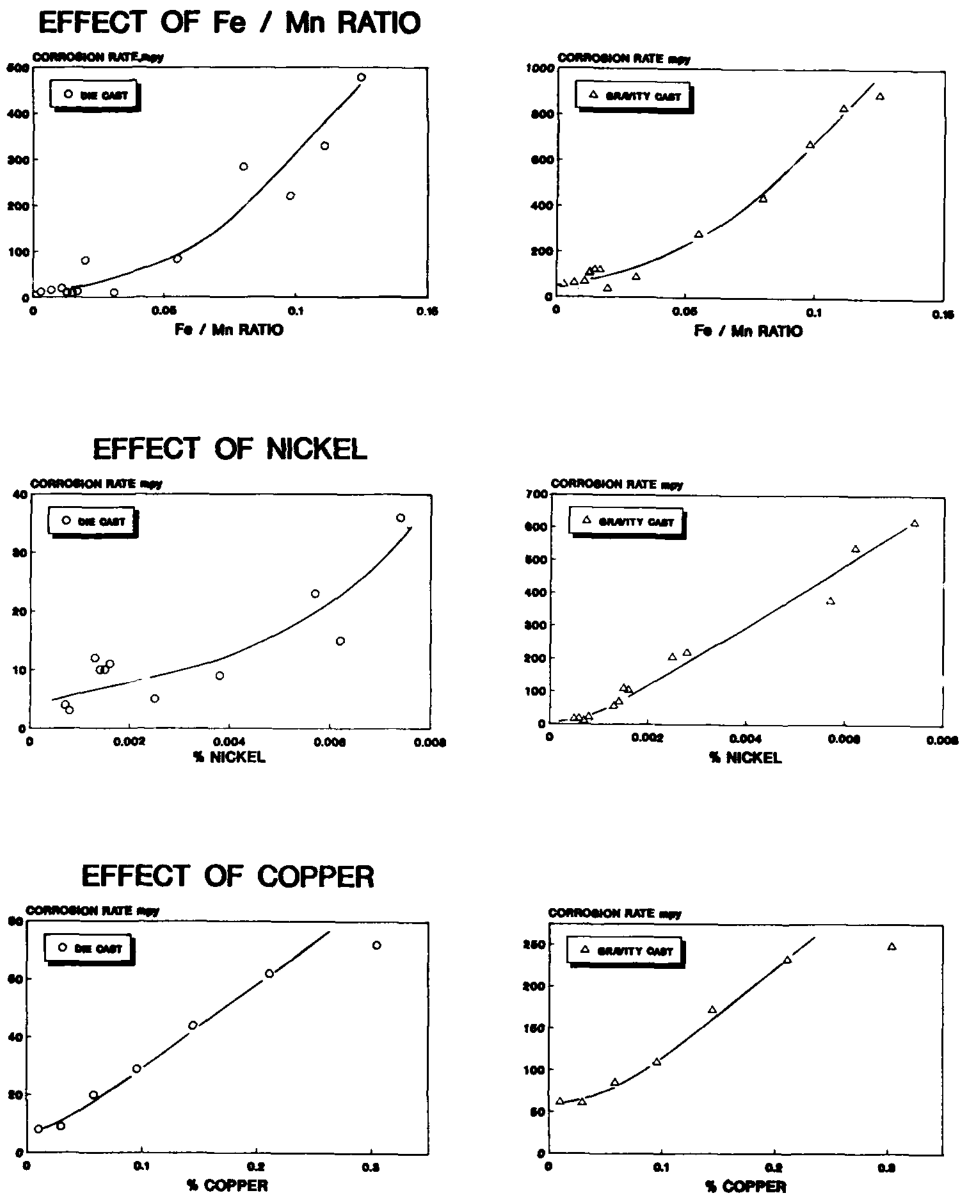

Figure 2: The Effects of the Fe/Mn Ratio, Nickel and Copper on the Salt Spray Corrosion Rate of AZ91 Magnesium Alloys (Redrawn From Ref (9)).

These recently developed high purity magnesium alloys have been shown to provide excellent corrosion resistance for many commercial applications (13). The beneficial effects of lower impurity specifications have now also been extended to other magnesium alloys such as the more ductile AM60 alloy (nominally 6% Al, 0.25% Mn) (14).

In spite of the significant advances made by the introduction of higher purity alloys, there remains several critical and value added applications where corrosion concerns necessitate heavy protective coatings or preclude magnesium entirely. Hence, there is a need to establish if the use of ultra-high purity magnesium alloys are capable of providing the exceptionally low and consistent corrosion rates required for these critical applications.

To meet the corrosion requirements of particularly critical applications, Timminco Metals has proposed a new generation of super and ultra purity alloys, an example of which are AZ91 SX and AZ91 UX as given in Table II. To provide a greater degree of assurance, these newly developed alloys specify iron, nickel and copper impurities to four decimal points (i.e. the nearest part per million).

Table II: Chemical Specifications for New Generation Super and Ultra Purity AZ91 Alloys

Alloy	Designation	Specification Max %			Min %
		Fe	Ni	Cu	Mn
New Alloys AZ91SX	TIMMINCO Super Purity	0.0024	0.0010	0.0024	0.17
AZ91UX	TIMMINCO Ultra Purity	0.0015	0.0010	0.0010	0.17

One of the objectives of this study is to quantify the improvements in corrosion resistance that can be attained at the super and ultra purity magnesium alloy impurity levels.

THE EFFECTS OF ULTRA-HIGH PURITY; CURRENT STUDY:

(i) Experimental Program

To investigate the effects of ultra-high purity, a series of AZ91 alloys of ranging impurity levels were die cast into 6" x 4" x 1/16" (15 cm x 10 cm x 0.16 cm) corrosion test panels on a commercial hot chambered die casting machine.

These panels were subjected to a rigorous examination to minimize unexplainable variability in the corrosion data. The chemical composition of each visually acceptable panel was determined by removing a 2" portion from its bottom and spectrometrically analyzing it in 3 locations. The final selection of panels was made after x-ray examination to ensure the absence of porosity and other imperfections that may lead to spurious results.

Selected test panels were dimensioned, finished to a 120 grit surface, washed with deionized-distilled water, degreased and weighed. They were then suspended from a glass rod in a salt spray cabinet which meets the requirements of ASTM B117 for a total of 240 hours (10 days). The position of the coupons was shifted periodically to ensure uniform exposure.

After exposure, the panels were rinsed with distilled water, dried and cleaned of adherent corrosion products by immersion in hot 20% chromic acid plus 1% silver nitrate for 1 to 2 minutes (ASTM G1). The panels were quickly dried and reweighed.

In accordance with G1 procedures, the corrosion rate in mils per year (thousands of an inch per year) was calculated with equation (1);

$$\text{Corrosion Rate (mpy)} = 3.45 \times 10^6 \; W/(A \times T \times D) \qquad \ldots (1)$$

where;
W is the measured weight loss in grams
A is the panel's total surface area in cm^2
T is the exposure time in hours
D is the density of the alloy in gm/cm^3

These corrosion tests were conducted in an independent laboratory at the Ontario Research Foundation, Mississauga, Ontario (Reports CS 138-86 and CS 111-88).

(ii) Data Analysis

To broaden the range of compositions covered by this investigation, data from this study were combined with those reported in the literature by Hillis et al (6,9). By combining these two independent investigations, a single, comprehensive data matrix consisting of 83 corrosion test panels was created (see Appendix I).

Table III: Range of Compositions and Corrosion Rates in the Combined Data Matrix

Study	Parameter	Investigated Range	
		From	To
Current	Nickel, %	0.0001	0.0014
	Copper, %	0.0001	0.0115
	Iron , %	0.0011	0.0162
	Fe/Mn , -	0.0076	0.0383
	Corr. Rate, Mils/Yr	0.4	40.0
	No. of Panels	53	
Hillis et al	Nickel, %	0.0007	0.0135
	Copper, %	0.0019	0.3040
	Iron , %	0.0012	0.0151
	Fe/Mn , -	0.0033	0.1258
	Corr. Rate, Mils/Yr	8.0	478
	No. of Panels	30	

As shown in Table III, the combined data matrix used in this study covers a wide range of chemical compositions from exceptionally low levels of nickel, copper and iron (1, 1 and 11 ppm respectively) to a relatively impure grade of AZ91.

Multiple regression analysis was used to statistically develop the best model to account for the combined effects of heavy metal impurities on the corrosion rate (equation 2).

$$\log(\text{corrosion rate, mils/yr}) = 1.5657 + 0.4931 \log(\%\ Cu) + 168.8215\,(\%\ Ni) + 18.8154\,(Fe/Mn) \qquad \ldots (2)$$

$r^2 = 0.83$ Standard Error : 0.275
F Ratio: 124.85 ; Degrees of Freedom: 3,79

This logarithmic equation between impurities and corrosion rate is in agreement with the exponential relationships shown graphically in the literature (Figure 2). To the author's knowledge, equation (2) is the first mathematical expression to quantitatively predict the combined effects of iron, nickel and copper on the corrosion rate of AZ91 magnesium alloys.

Figure 3 compares the corrosion rates calculated by equation (2) with those observed by experimentation. As indicated in this figure, the regression model fits the corrosion data over the entire range from less than 1 to in excess of 470 mils/yr. The agreement between experiment and calculation is judged to be more than adequate considering that data from two completely independent studies were combined for regression.

DISCUSSION

Equation (2) was used to statistically predict the combined effects of iron, nickel and copper impurities on the corrosion rate of die cast AZ91 magnesium alloys.

(i) The Effects of Impurities on the Corrosion Rate:

(a) Current Commercial High Purity Die Cast Alloys (AZ91D and AZ91X):

Figure 4 illustrates the combined effects of copper and iron on the corrosion rate of AZ91 alloys containing 0.15% manganese and 0.0014% nickel. The diagonal isocorrosion rate lines ranging from 30 to 1 mils/yr have been calculated with equation (2) and specify the statistically predicted corrosion rates at various impurity levels. The beneficial effects on corrosion of simultaneously lowering the copper and iron contents of AZ91 are evident from this figure.

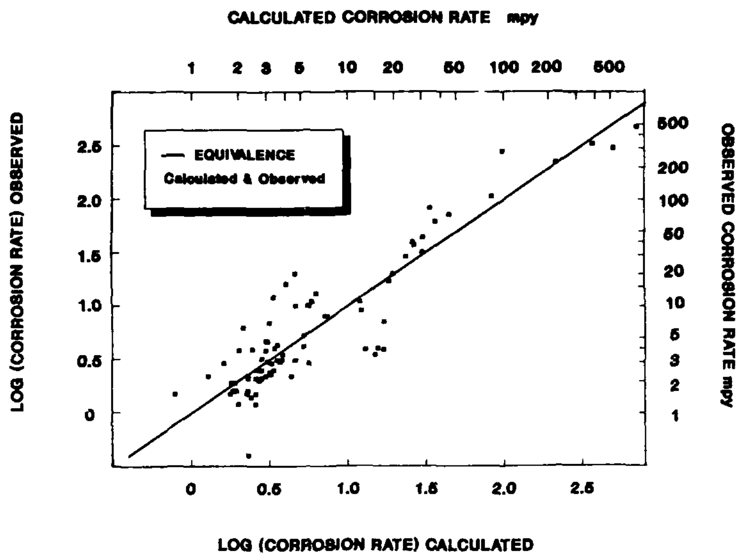

Figure 3: Comparison Between Calculated (Equation 2) and Observed Corrosion Rates.

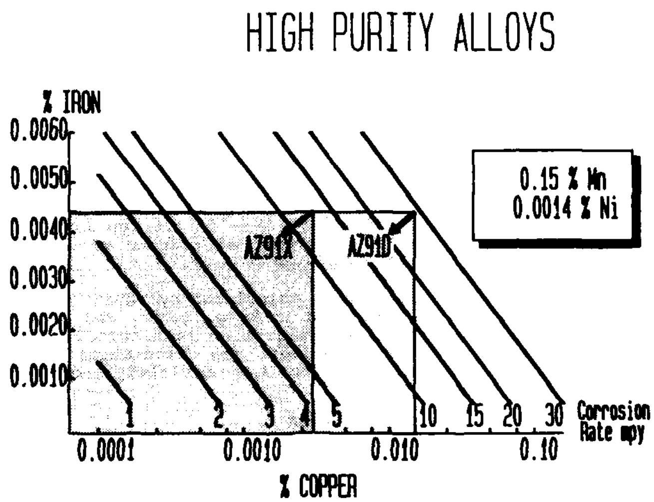

Figure 4: The Combined Effects of Copper and Iron on the Corrosion Rate of Current Commercial AZ91 High Purity Alloys Which Specify a Maximum Nickel of 0.001%.

Since the corrosion rates shown in Figure 4 have been calculated at the maximum nickel specification limit for the AZ91D and AZ91X alloys, (0.001 % Ni), the intersection point joining the maximum specification limits for copper and iron (Table I) specifies the maximum corrosion rate expected for these high purity alloys.*

As indicated by the intersection point in this figure, properly designed AZ91D high purity alloy castings would be expected to have corrosion rates of 28.5 mils per year or less.

The lower copper in the AZ91X high purity alloy (0.003% max) reduces its anticipated maximum corrosion rate to 13.7 mils/yr.

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* In this analysis, iron, nickel and copper are taken to the nearest part per million (4 decimal points). For example, the chemical specifications listed in Table I, 0.001% Ni and 0.004% Fe, can be satisfied by rounding down primary metal ingots analyzing at 0.0014% Ni and 0.0044% Fe, respectively. These latter analyses represent the maximum impurity levels which can be shipped by primary metal producers based on a 3 decimal point specification and, hence, are used in the calculation of the maximum corrosion rates shown in Figure 4.

(b) New Generation Super and Ultra Purity Alloys (AZ91SX and AZ91UX):

Figure 5 illustrates the effects of iron and copper impurities on the corrosion rate of the newly developed AZ91SX and UX alloys. As noted in Table II, impurities in these alloys are specified to the nearest part per million (4 decimal points).

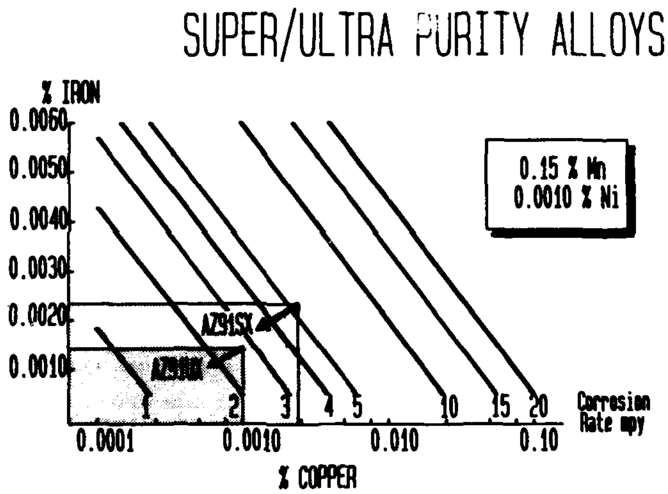

Figure 5: The Combined Effects of Copper and Iron on the Corrosion Rate of New Generation AZ91 Super and Ultra Purity Alloys.

As in Figure 4, this graph specifies 0.15% Mn which would be typical of many die cast components. However, in Figure 5 the isocorrosion rate lines are calculated for 0.0010% nickel which is the maximum specification limit for the AZ91SX and UX alloys.

As before, the intersection point between the maximum specification limits for iron and copper represents the highest corrosion rate that can be anticipated for these alloys. As shown in this figure, the expected maximum corrosion rate for super purity AZ91SX is 5.5 mils per year. This is further decreased to 2.8 mils per year for ultra purity AZ91UX.

The exceptionally low corrosion rates attained with the super and ultra purity AZ91SX and AZ91UX are due to the simultaneously low levels of iron, copper and nickel in these alloys.

(ii) The Effect of Impurities on the Variability in Component-to-Component Corrosion Rates:

Figures 4 and 5 illustrate that simultaneously lowering the upper specification limits for iron, copper and nickel significantly decreases the anticipated maximum corrosion rate of castings made from AZ91 magnesium alloys.

In addition to decreasing the absolute magnitude of the corrosion rate, lowering impurity specification limits also minimizes the expected variability in component-to-component corrosion rates.

In Figures 4 and 5, the shaded regions represent the range of corrosion rates that can be expected for each alloy based on their impurity specification limits. The corrosion rate of each component will depend on the actual chemical composition of the primary alloy ingots which varies within the specification range.

For example, the shaded region associated with AZ91D in Figure 4 illustrates that depending on the actual chemical analysis of the primary alloy ingots used by the die casting foundry, component-to-component corrosion rates could vary anywhere from a low of about 1 mil per year to, in the worst case, 28.5 mils per year.

Reducing the iron, nickel and copper impurity specification limits decreases the variability in component-to-component corrosion rates. For example, as shown by the shaded regions in Figure 5, die cast parts made from the newly developed super purity AZ91SX can be expected to have corrosion rates ranging from a low of about 1 mil per year to a high of 5.5 mils per year. This range in corrosion rates is still further decreased to between about 1 to 2.8 mils per year for AZ91UX ultra purity alloy.

(iii) Significance of the Fe/Mn Ratio:

Regression analysis in the current study confirms previous reports (9,10) that the Fe/Mn ratio in the casting is more highly correlated with the corrosion rate than is the iron analysis. Manganese appears to have a twofold effect, first precipitating iron to the solubility limit prior to casting the melt and, second, coating the remaining iron particles during solidification thereby inhibiting their cathodic corrosion effect in the final casting (15).

The solubility of manganese in AZ91 is strongly dependent on the iron content of the alloy and the melt temperature (9). The lower metal temperatures encountered in many die casting foundries compared to primary metal operations often leads to a significant manganese precipitation during primary ingot remelting. In this investigation, the manganese content of the die cast corrosion test panels averaged about 0.15% which represents only about 50% of the original manganese contained in the primary metal ingots.

Because of the significant precipitation of manganese that can occur during ingot remelting, the Fe/Mn ratio in the primary metal ingots is not a good indicator for predicting the corrosion resistance of the final casting.

Hence, even though the corrosion rate is dependent on the Fe/Mn ratio in the casting, the addition of large amounts of manganese to the primary metal will not negate the harmful effects of excessively high iron levels. In view of the propensity for manganese precipitation, reducing the iron content of the primary metal and following good foundry practice to minimize iron pickup during processing are the only effective ways of ensuring low corrosion rates.

(iv) Visual Appearance of Corrosion Test Panels:

Figure 6 illustrates the visual appearance of AZ91 magnesium alloy test panels of various impurity levels after 10 days exposure to salt spray.

As shown in this photograph;

- at 31.9 mils per year, surface pitting is heavy and deep; however, no perforations exist as would have been the case with the previously standard purity AZ91B alloy.

- at 6.9 mils per year, surface pitting is significantly reduced; however, localized deep pits are still evident.

- at 5.3 mils per year, surface pitting is minimal and not deep; the sample is more blemished than pitted. Sample identification scribe marks are clearly visible.

- at 2.9 mils per year and less, no pits are evident. The panel surface has a very fine roughened appearance and is clean enough to reveal the flow pattern of the liquid metal as it was injected into the die cavity.

The test panels shown in Figure 6 are typical in appearance to others at the stated corrosion rates. Of the 53 panels used in the Timminco salt spray tests, 48 panels had corrosion rates of 5.3 mils per year or less while 30 panels had corrosion rates equal to or less than 2.9 mils per year (see Appendix I).

From this photograph, it is quite evident that substantially improved corrosion resistance can be realized by progressively specifying high purity, super purity and ultra purity AZ91 magnesium alloys. Not only is the corrosion resistance higher, but the degree of variability in part-to-part corrosion rates is significantly reduced by specifying alloys with tighter impurity specification limits.

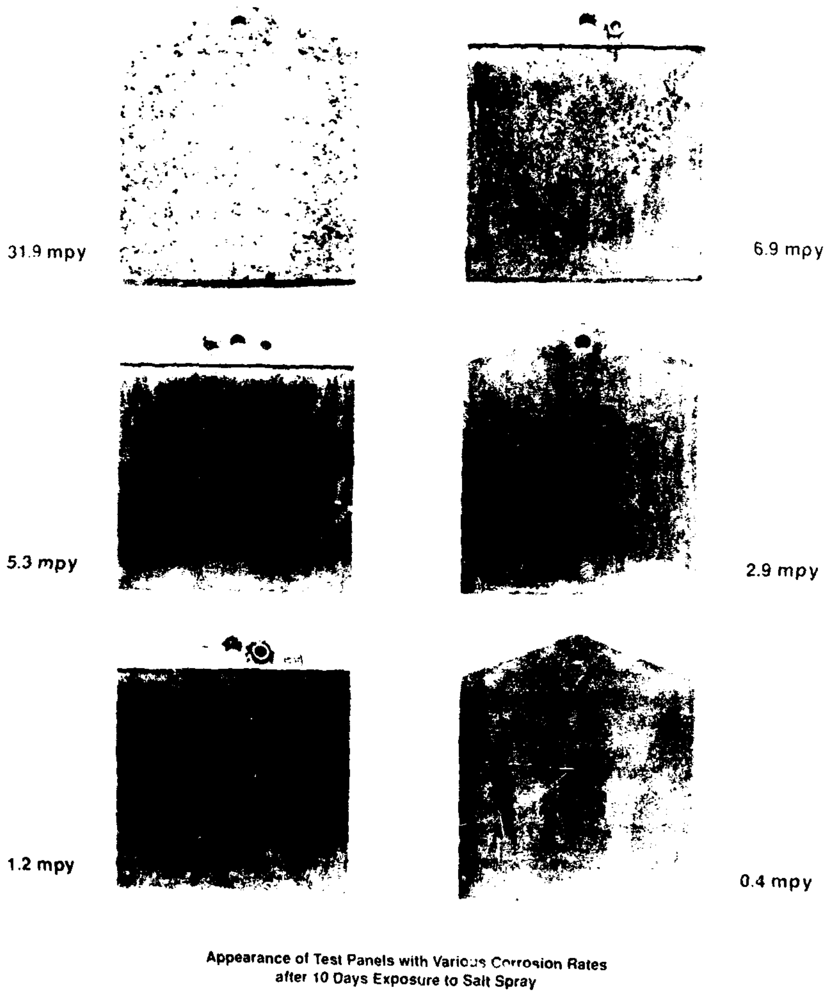

Figure 6: Visual Appearance of AZ91 Magnesium Alloy Test Panels of Varying Purity After 10 Days Exposure to Salt Spray.

CORROSION RESISTANT MAGNESIUM ALLOYS: A NEW ALTERNATIVE FOR AIRCRAFT DESIGNERS

As pointed out by D. Little (16) in his keynote address to the 3'rd Conference on Aluminum-Lithium Alloys, the rewards from reducing aircraft design weight can be significant. These include reduced engine size which in turn leads to reduced fuel consumption which in turn can result in an overall downsizing of the aircraft. For modern long range aircraft, Little estimates that for every 1% saving in empty design weight, the increase in available revenue payload carrying capacity is almost 4%.

In an effort to reduce take-off weight, aircraft designers and engineers are now examining a host of advanced materials and structures including metallic alloys, advanced plastics and composite materials.

Figure 7 illustrates the potential weight savings that can be accrued by improving materials properties (17).

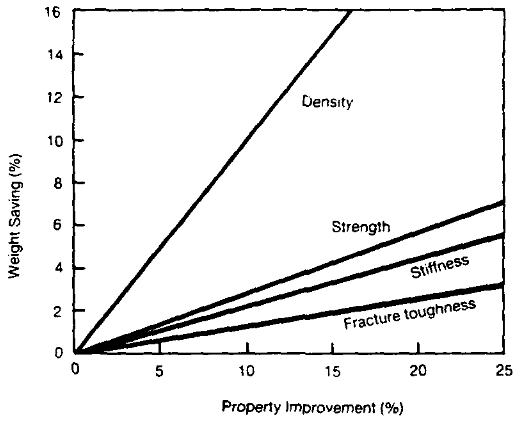

Figure 7: Weight Savings Achieved by Improved Materials Properties (17).

As indicated in this figure, substituting materials of a lower density has the most significant impact on weight saving (1 for 1 relationship). Introducing materials with increased strength, stiffness and fracture toughness can also reduce weight but to a much lesser degree.

For example, replacing an aluminum casting with an identical magnesium component would reduce weight by about 34% strictly on the basis of relative density differences.

If the part were redesigned to maintain a constant stre. :. stiffness, the weight savings associated with magnesium would be about 28%. However, depending on the application, it may be possible to take advantage of magnesium's excellent castability thereby enabling net shape casting of thin walled sections which may lead to weight savings as high as 40%.

The availability of highly corrosion resistant magnesium alloys offers significant opportunities for reintroducing lightweight magnesium castings into military and commercial aircraft. Depending on the particular corrosion sensitivity of the application, aircraft design engineers can now specify either high, super or ultra purity magnesium alloys. Components such as seat frames, cockpit parts, wheels, housings, etc. can be readily die or gravity cast from these corrosion resistant magnesium alloys.

In addition, the performance of protective coatings which may be applied to the surface of the component is further enhanced with these alloys. For example, the use of a more highly corrosion resistant metal substrate minimizes the likelihood of corrosive attack at coating imperfections, along scratches or at chip marks and along machined surfaces and joints.

In view of the excellent and progressively improving corrosion resistance of high purity and the newer generation super and ultra purity alloys, the increased use of lightweight magnesium castings in modern aircraft is worthy of review.

SUMMARY

Considerable research has been conducted by the magnesium industry to improve the corrosion resistance of magnesium alloys. These studies have led to the introduction of high purity alloys which have been shown to provide excellent corrosion resistance in many commercial applications.

Timminco Metals has now introduced super and ultra purity magnesium alloys which have exceptionally high and consistent corrosion resistance. These new generation magnesium alloys have been designed to meet the special requirements of particularly critical or value added components where corrosion is a prime concern.

Figure 8 summarizes the results obtained from multiple regression analysis relating the effects of heavy metal impurities to the salt spray corrosion rate of these higher purity AZ91 magnesium alloys. As shown in this figure, specifying alloys with progressively tighter impurity specification limits;

- significantly lowers the absolute magnitude of the corrosion rate
- significantly reduces the range in component-to-component corrosion rates (i.e. from a low of about 1 to a high of 2.8 mils/yr for AZ91UX compared to about 1 to 28.5 mils/yr for AZ91D)

The corrosion resistance of die cast high purity AZ91D magnesium alloys has been reported to be equivalent to or better than that of die cast 380 aluminum (12 to 44 mils/yr) and cold rolled steel (30 to 49 mils/yr) as measured by similar salt spray tests (9,10).

Similar tests with new generation super and ultra purity magnesium die castings indicate an even higher degree of corrosion resistance combined with exceptionally low variability in part-to-part corrosion rates. Corrosion tests are now underway to confirm the improvements associated with these new generation alloys in gravity castings.

While the absolute magnitude of in-service corrosion rates may differ from those measured on test panels in the laboratory, the results from these ASTM standard salt spray tests should provide a good indication of the relative differences between the corrosion resistances of the respective alloys.

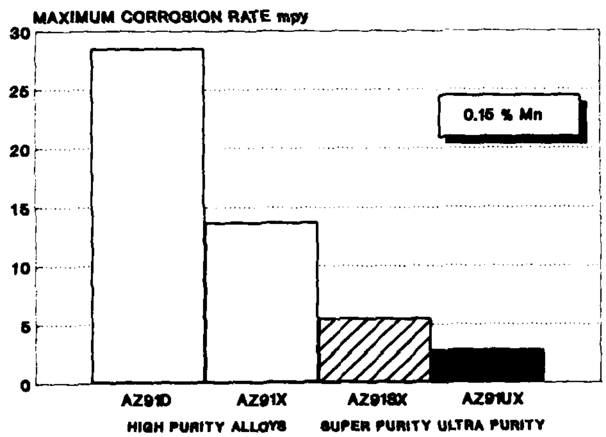

Figure 8: The Expected Maximum Corrosion Rates for Current High Purity and New Generation Super and Ultra Purity AZ91 Alloys.

Design engineers now have the opportunity of specifying either high, super or ultra purity magnesium alloys depending on the corrosion sensitivity of each particular application. To ensure that the excellent corrosion resistance of these alloys is realized in-service, designers must also take advantage of the well established design, finishing and coating practices that have been developed by the magnesium industry.

With the advent of these highly corrosion resistant alloys, the role of magnesium die and gravity castings in modern aircraft construction, particularly in cargo, cabin and cockpit related parts, should be re-evaluated. Weight reductions as high as 40% can be achieved by replacing conventional aluminum castings with these new, advanced highly corrosion resistant magnesium alloys.

ACKNOWLEDGEMENTS

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APPENDIX I

SALT SPRAY CORROSION DATA

(A) TIMMINCO SALT SPRAY CORROSION DATA

Panel	Chemical Analysis				Fe/Mn	Corrosion Rate
	Fe	Ni	Cu	Mn		Mils Per Year
1	0.0152	0.0011	0.0085	0.41	0.0371	37.3
2	0.0162	0.0010	0.0090	0.44	0.0368	40.0
3	0.0162	0.0012	0.0090	0.42	0.0383	31.9
4	0.0034	0.0012	0.0110	0.21	0.0164	3.9
5	0.0052	0.0014	0.0110	0.25	0.0210	7.1
6	0.0050	0.0014	0.0110	0.24	0.0208	3.9
7	0.0028	0.0014	0.0110	0.16	0.0178	3.5
8	0.0032	0.0014	0.0115	0.17	0.0183	4.0
9	0.0020	0.0008	0.0030	0.18	0.0111	3.1
10	0.0022	0.0011	0.0032	0.18	0.0124	2.9
11	0.0022	0.0008	0.0034	0.18	0.0124	4.2
12	0.0024	0.0008	0.0030	0.17	0.0139	5.3
13	0.0016	0.0007	0.0013	0.16	0.0100	3.2
14	0.0015	0.0007	0.0013	0.16	0.0092	2.0
15	0.0015	0.0007	0.0013	0.15	0.0100	2.5
16	0.0017	0.0008	0.0013	0.17	0.0106	2.2
17	0.0020	0.0007	0.0019	0.16	0.0121	3.0
18	0.0018	0.0007	0.0019	0.14	0.0126	3.1
19	0.0016	0.0007	0.0019	0.14	0.0110	3.1
20	0.0016	0.0007	0.0018	0.17	0.0096	2.3
21	0.0026	0.0007	0.0014	0.19	0.0144	4.3
22	0.0026	0.0004	0.0013	0.18	0.0141	4.7
23	0.0030	0.0006	0.0010	0.19	0.0158	4.6
24	0.0013	0.0001	0.0013	0.17	0.0076	3.8
25	0.0016	0.0005	0.0022	0.19	0.0084	6.9
26	0.0013	0.0006	0.0013	0.17	0.0076	3.9
27	0.0017	0.0007	0.0016	0.19	0.0089	3.8
28	0.0013	0.0008	0.0013	0.17	0.0076	2.5
29	0.0011	0.0007	0.0012	0.15	0.0073	1.4
30	0.0011	0.0004	0.0014	0.15	0.0073	2.1
31	0.0016	0.0004	0.0008	0.19	0.0084	1.6
32	0.0015	0.0006	0.0009	0.17	0.0088	1.2
33	0.0014	0.0005	0.0007	0.17	0.0082	1.5
34	0.0017	0.0005	0.0008	0.18	0.0094	1.2
35	0.0016	0.0006	0.0010	0.15	0.0107	1.5
36	0.0019	0.0005	0.0008	0.15	0.0127	0.4
37	0.0022	0.0005	0.0014	0.16	0.0138	2.4
38	0.0017	0.0005	0.0009	0.15	0.0113	2.2
39	0.0019	0.0006	0.0010	0.16	0.0119	1.2
40	0.0017	0.0006	0.0006	0.16	0.0106	1.9
41	0.0020	0.0006	0.0012	0.17	0.0118	2.1
42	0.0026	0.0004	0.0008	0.16	0.0163	2.1
43	0.0027	0.0005	0.0005	0.15	0.0180	1.6
44	0.0025	0.0005	0.0006	0.16	0.0156	1.5
45	0.0022	0.0005	0.0007	0.13	0.0169	1.5
46	0.0030	0.0005	0.0009	0.13	0.0231	3.5
47	0.0028	0.0005	0.0008	0.13	0.0215	2.5
48	0.0033	0.0005	0.0013	0.15	0.0220	2.2
49	0.0030	0.0002	0.0007	0.12	0.0250	2.9
50	0.0032	0.0005	0.0002	0.14	0.0229	1.9
51	0.0031	0.0003	0.0002	0.14	0.0221	2.9
52	0.0031	0.0004	0.0003	0.15	0.0207	1.6
53	0.0032	0.0005	0.0001	0.14	0.0229	2.2

(B) PUBLISHED SALT SPRAY CORROSION DATA
(HILLIS et al)

Panel	Chemical Analysis %				Fe/Mn	Corrosion Rate Mils Per Year
	Fe	Ni	Cu	Mn		
1	0.0012	0.0013	0.0021	0.36	0.0033	12
2	0.0031	0.0014	0.0020	0.42	0.0074	16
3	0.0045	0.0014	0.0019	0.41	0.0110	20
4	0.0051	0.0015	0.0021	0.39	0.0131	10
5	0.0048	0.0016	0.0021	0.35	0.0137	11
6	0.0062	0.0013	0.0021	0.35	0.0177	13
7	0.0050	0.0013	0.0022	0.34	0.0147	10
8	0.0026	0.0014	0.0022	0.14	0.0200	8
9	0.0043	0.0014	0.0023	0.14	0.0307	11
10	0.0072	0.0013	0.0023	0.13	0.0554	83
11	0.0104	0.0013	0.0023	0.13	0.0800	284
12	0.0127	0.0013	0.0024	0.13	0.0977	221
13	0.0144	0.0013	0.0023	0.13	0.1108	329
14	0.0151	0.0013	0.0023	0.12	0.1258	478
15	0.0013	0.0013	0.0099	0.44	0.0030	8
16	0.0012	0.0013	0.0295	0.42	0.0029	9
17	0.0019	0.0015	0.0587	0.45	0.0042	20
18	0.0017	0.0014	0.0960	0.42	0.0040	24
19	0.0019	0.0015	0.1450	0.45	0.0042	44
20	0.0021	0.0014	0.2112	0.43	0.0049	62
21	0.0022	0.0014	0.3040	0.40	0.0055	72
22	0.0024	0.0007	0.0019	0.24	0.0100	4
23	0.0011	0.0008	0.0025	0.30	0.0037	3
24	0.0012	0.0013	0.0021	0.36	0.0033	12
25	0.0045	0.0014	0.0019	0.41	0.0110	10
26	0.0051	0.0015	0.0021	0.39	0.0131	10
27	0.0048	0.0016	0.0021	0.35	0.0137	11
28	0.0009	0.0048	0.0042	0.26	0.0035	17
29	0.0009	0.0087	0.0042	0.26	0.0035	107
30	0.0009	0.0133	0.0042	0.26	0.0035	300

SOME GENERAL THOUGHTS FOR THE FUTURE AIRWORTHINESS REQUIREMENTS OF CASTINGS

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SUMMARY

These "notes" were the outcome of a contribution made "extempore" at the meeting.

The author felt that general aspects of "airworthiness requirements and casting development" for aircraft also had a bearing upon the viability or otherwise of castings in structures, other than the obvious influence of casting factors and mechanical test requirements, and has attempted to put them into perspective.

INTRODUCTION

The general reaction by founders and designers when considering the airworthiness requirements for castings is to debate the special factor requirements that have been traditionally greater than for other methods of manufacture. However, as shown by the Chairman's preface to this Workshop, several other matters, perhaps of equal importance, are involved and must be addressed if more castings are to be used in the future.

THE CASTING FACTOR

Historically, it is questionable whether the factor specified in the different categories was entirely related to the material of the casting. They were and are of maximum benefit where stiffness and complexity of geometry are involved. Consequently, they were difficult to analyse with respect to stress distribution and the "structural test" static requirements for the different design cases therefore involved proof of attainment of the design with the material as used.

While this Workshop has contributed to the already strong evidence that the casting methods overall have much improved, it should also be said that the ability of the structural engineer to make accurate interpretation within the structure of the loads derived from aerodynamic assessment, and to make very accurate detailed analysis of the resulting stress distribution within the given design, has improved many times also.

It is therefore from consideration of both points of view that the ability to reduce the historical "factor", safely, must be considered.

The BCAR shown in the paper by M.M. Sancho refers to the simple calculated factor of 2 as acceptable without test.

This was more likely in the past to have been achieved automatically without too much effort on the designer's part, due to the inability of the foundries at that time to achieve thin section and scantlings and with close tolerance, rather than a deliberate attempt to design to achieve high factors to alleviate the need for costly structural testing.

In those days, often with short production runs of an aircraft type, these development costs may have taken a significantly greater proportion of the piece part cost than with today's longer runs.

As has been pointed out in an early paper at this conference, with the lower factors or even unit factors now being agreed with the Airworthiness Authorities, with only one structural test sample (still partly to prove material and partly to confirm design), castings will probably be designed and used for exactly the same reasons as before, with actual factors on test greater than 1.

If that was the purpose of this Workshop, to allow the use of castings on an equal opportunity with wrought metallic materials, then this is already achieved.

There are other aspects, however, which influence the matter. It has been suggested that there is a greater need for safety with civil aircraft than for military vehicles, but does this mean a higher "casting factor" for civil design? Since the original airworthiness requirements for castings were drafted, the aspect of fail-safe, with the consequent dual load paths and redundant structures, have become the basis of the design. Surely these must be considered, and significantly affect the need for special factors with castings, if any more influence were necessary to enable a factor of unity to be accepted.

COST

Even before this move to better quality castings and more equality with other forms of manufacture over the years, for civil aircraft at least, a cost exercise on components complete on the airframe was not always as favourable to the use of castings as might be supposed at first sight. Even with the simple requirement of X-ray, penetrant flaw detection and melt control as it has been operated, it has often been the case that the cost of the testing represented from one third upwards the total cost of the casting. It is therefore essential, if new sets of airworthiness rules are to enable the greater use of castings to keep costs down. It will not be productive if the costs of manufacture escalate and the cost of testing push the product once again into the background.

I would submit that the achievement of the Authorities' willingness over past years to relax the casting test factor, as has happened, has largely been brought about by improving the control of manufacture in the state of the art as it is, and not the result of the new and specialised improved technologies we have heard about in this Workshop, for instance.

This has resulted from the use of quality assurance techniques to ensure that whatever was supposed to be done is done reliably, but without the need for increased testing to prove it.

PROPERTIES

The accent of modern metallurgical papers, laudably to improve the metallurgical quality and consistency with higher properties, has possibly not influenced the airworthiness requirements that much. They are, of course, justified in themselves as reduced property scatter contributes to the use of higher design minima, as does the improvement of properties, which of course helps to make the cast material more cost effective.

In general, cast materials have a long way to go before they have overcome this current disadvantage of low properties relative to the long and L.transverse wrought properties.

This is not nearly such a disadvantage in the wrought short transverse properties however and, bearing in mind that castings generally have a better chance of satisfying complex shapes, becomes very significant when making the choice.

To permit equality of castings with wrought products for the designers' use, the qualified materials must be tested and analysed to provide the A & B values, etc, for modern design.

Whether or not this implies that these results must be monitored by frequent cut-up tests, say from every melt, as has been suggested, is open to question. Wide variations of properties can occur, for similar reasons to that of castings, in forgings, and even thick section wide plate, but we do not have a continuing cut-up testing operation to monitor these.

Of course, proper analysis of the product as made, is necessary for the designer to be aware of what the product can provide, but let us not price castings out of the market just when there is an impetus to make the best use of this form of manufacture that we can.

May I therefore, in this range of technology, seek a course of moderation. After all, large constructors rarely purchase products from a single source these days. They cannot afford to do so.

Very specialist foundries with unique, often "secret" internal techniques have not necessarily been used by some large contractors as there must always be some slight risk of problems with the individual component, the workforce, the company, etc., which could jeopardise delivery and could put an aircraft production line at risk, especially as the complex form of castings, once approved and built into the design, are difficult to replace by manufacture by some other method - machine from solid, forging, assembly from detailed formed parts.

This dilemma, related to rapidly advancing technology by individual firms, is well known and has arisen with plate, paint, resins, etc, already.

CORROSION

Another requirement of the airworthiness of the aircraft is that it shall have adequate resistance to its total working environment. Today this also includes the previously neglected influence of corrosion upon fatigue behaviour, corrosion fatigue. Ferritic/ martensitic steels are possibly most notorious in this respect, but non ferrous materials are significantly affected also.

This means that more than ever before adequate protection must be applied which can eliminate the corrosion fatigue aspects as well as protect against what, I call, the "static corrosion" influence.

It has been demonstrated elsewhere that high tensile steel can be protected by suitable pretreatment and resin protection, and so can magnesium alloys. Corrosion has been the bane of the aircraft user for years, yet most of the components by far have been of aluminium. Galvanic protection can be simply provided, to allow magnesium alloys safe and reliable contact with other more noble metals.

Last year in Boston, after studying case histories and extensive laboratory comparative tests of protectives, or lack of them, the US Materials Command agreed that magnesium alloys, properly protected, should be allowed in new designs, and that the past problems were related to lack of attention to simple design principles, and not unique to magnesium alloys.

In the founders' and constructors' interests for the greater use of castings, let us therefore not neglect the benefits that correctly chosen magnesium alloys can provide when coupled with good modern protectives.

The Authorities have said that they are moving ever toward the study of the needs of individual components, and therefore this should again be widened to enable properly protected magnesium to be used to advantage also.

X-RAY

For many years, I have considered methods of radiographic inspection with images projected upon a screen and without the expensive use of permanent film, which records only one view.

It is believed that with modern methods and including means of "intensifying" the image, perhaps even assistance in analysing it, much cheaper and perhaps more critical X-ray examinations could be achieved.

While in the past the filmed record has been used to monitor the quality of the radiographic examination as a Q.A. activity in order to fulfil the contractor's responsibility for the foundry in this respect, it is believed that other means of "checking" could be introduced. With today's ability to analyse failures metallurgically, the film record is not really necessary to identify a defect. Indeed, it can only do so when the operators missed it, and not when the radiographic technique used missed it.

As this essential method of quality assessment features so highly in the cost of castings, it would seem well worthwhile rethinking the methods of achievement and then making any necessary changes to the requirements to permit the use of different methods.

SURFACE IMPERFECTIONS

The influence of surface defects or surface quality is usually dominant in most service failures, especially when they are fatigue related. Fortunately on castings the nature of linear surface defects as well as depressions, etc, as by shrinkage and porosity at the surface are easily and reliably seen by penetrant N.D.T. methods, whereas with forged products surface defects can be forged together and are so tight that penetrant N.D.T. will not disclose them.

Fatigue has been much discussed for future component integrity, and to a large extent this is likely to be more influenced by the texture and quality of the surface than, say, be affected by differences of mechanical properties (scatter) or even surface roughness.

One simple way of eliminating this variability is not to spend money on providing exceptionally fine, smooth surface finishes, but to ensure that the final surface treatment before final protectives are applied, is a controlled inert blast process. Clearly the non-destructive penetrant inspection must be done before this operation.

It has the added advantage that the reduction of fatigue performance introduced by various chemical or electrochemical processes in the cleaning and surface preparation of castings (and other components) is also mitigated by a controlled blasting process.

Of course it is another cost, although the process advocated is not the critical shot peening procedures with their very costly quality control. Equally it need not be considered for those parts not thought to be significant from a fatigue viewpoint, but bearing in mind that it virtually removes concern for normal reasonable surface roughness worries, it is usually safer and better to adopt such a process for all components and not just those identified as fatigue sensitive.

SPECIFICATIONS AND MATERIAL DEVELOPMENTS

a) Fusion Welding

Not all materials are readily weldable, and certainly wrought alloys cannot be welded at all, if my definition of weldability, which says that "the properties of the weld must not be less after welding and the normal heat treatment than that of the material before welding" is applied.

The application of welding, for repair, within these terms of reference is possible with several of the aluminium and magnesium cast alloys available today. Of course the use of the process needs development and experience with operators for the relevant alloy and a procedure of approval and production quality control to ensure that sound welds of the correct properties are achieved.

Many years of experience in this field have shown that such procedures are worthwhile and extremely cost effective, whether they recover castings otherwise unacceptable from some foundry defect, or due to incorrect machining, marking out or service problem, even modification to the shape, because of design change.

The total process/procedure can be so developed that with some alloys it is not necessary for design to consider the position of the weld relative to the casting, as may otherwise be the case of weld repair today.

It is recommended therefore that in alloy development and airworthiness requirements this aspect is considered. It can make all the difference in establishing a viable casting programme.

b) Material Specifications

Traditionally, metallic materials have tended to be one part general specifications, whereas non-metallic materials have been two part.

The first part contains a series of appropriate qualifying tests for the material, often prolonged and expensive, by which the attempt is made to identify the characteristics of the material and hopefully, if repeated later in production, would show whether changes of manufacture, however small, affected the material or not.

Possibly this difference between metals and non-metals developed in the belief that the older structural metals were well established and understood and the newer complex inorganic substances were not, with respect to mechanical property differences.

Today I feel few would argue the case. The more we learn, the less we find we know about our metals.

There is justification for adopting a two part system for this reason alone.

However the prime reason for introducing it here is that as many costly characterising tests can be made in part 1 of the specification as one likes, as they rarely need repeating on subsequent production, unless a manufacturing change is made.

(Exactly the same philosophy as the critical preparation of the technique sheet for manufacture now used universally, for all forms of products.)

The second part of the specification, the release part, should then contain the minimum number of the shortest possible tests, which will give reasonable confidence that the material and quality is that of the original product identified in part 1 of the specification.

In this way costs can be kept to a minimum. Equally importantly the total order, manufacture, release, delivery time can be kept to a minimum as well, a feature often critical in a production run, but which leads to reduced storage costs, etc, which with high capital interest charges contribute to the total cost all along the line.

In all these ways, therefore, I plead for moderation in looking at specifications and airworthiness requirements so that we really get cost effective improvements from the new technologies, and can use them in successful commerce.

If we do not, then we may not benefit either the founder or constructor by reviewing the airworthiness requirements.

COMMENTS FROM THE FOUNDRY SPECIALISTS

by

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The official and semi-official organisations gave a brief review of the areas of aircraft design in which castings can nowadays be used. Within this context the applicable casting factors were also referred to. From this it appeared that different criteria of assessment are used in different countries, and consequently, varying casting factors are applied.

A reason why these safety factors are incorporated, and why they are still specified today in spite of improved methods of design, production and inspection, did not emerge from the various lectures or other contributions to the proceedings.

The papers given by the group of aeronautics designers showed which structural components are currently in use or in development. The examples quoted, referred to military as well as to civil aviation. In addition, new developments in the field of aircraft construction were outlined and new targets set.

The aim is to equip primary aircraft components with castings, in order to make aircraft production more economical. All the parts shown however, were provided with the appropriate casting factors. These ranged from 1.1 to 1.5 and above.

On the other hand, the difficulties which have arisen in the course of developing structural castings in primary components were shown clearly. The subsequent improvements carried out on individual castings, as demonstrated in concrete examples, were necessary from a static as well as from a dynamic point of view. In the fields of metallurgy and casting technology too, steps hat to be taken to achieve the required improvements.

The extensive programme of lectures also contained contributions from the foundry industry demonstrating which development level and quality assurance measures are currently "state of the art" for primary aeronautics castings.

In recent years, the foundry industry has made decisive progress in the development and serial production of "stress-bearing thin-walled structural castings". This applies to the sand castings as well as to the investment casting process. The large cabin frames, housing pieces for cruise missiles and pylons are especially prominent in this respect, as are the large structural parts resulting from development programmes in the USA. A further example are the results of the German programme entitled "Economic Structural Technologies". The luggage hold door is also worthy of mention as an important milestone in the investment casting sector.

Notable advances have been achieved in the foundry through process refinement, new pouring and feeding techniques, the use of cold-setting sand, more accurate patterns and improved methods of melting and melt treatment. Casting, fettling, heat treatment and inspection procedures for aeronautics castings have all undergone radical change - in this case, synonymous with radical improvements.

The routines being used today by manufacturers of aeronautics castings can no longer be compared with those current in foundries 15 years ago, and still less with those of 20 - 30 years ago, when the casting factors, many of which are still in force today, may have been justified.

The foundry industry offers its assistance to aeronautics designers and material engineers in the creation of parts adapted to the technical requirements of the foundry and in ensuring that the most suitable materials are put to use. Modern design and pattern making processes (CAD/CAM). In conjunction with the solidification simulation of castings allow us to detect weak points at a very early stage and to take the necessary countermeasures.

Within the context of developing modern design and production processes, it is our view that the expert system, currently in use in so many sectors of industry, could also find application in foundry production thus becoming an important aid to the design engineer.

When we consider developments in the foundry field, both from the point of view of production and inspection the question inevitably arises as to whether the casting factor is still necessary when applied to aluminium and magnesium castings.

A further argument which should be taken into account in assessing the casting factor is that nowadays only companies which can achieve and maintain a certain level of quality are authorised to manufacture aircraft castings.

From the various contributions to the discussion, the distinct impression was gained that any change in the casting factor would be initiated by the official or semi-official authorities, as they are responsible for laying down the guidelines for aircraft design.

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The AGARD Structures and Materials Panel held a Workshop on Castings Airworthiness in Mierlo, Netherlands in the Fall of 1988 to consider whether a casting factor, as such, need still be applied to premium quality castings given the improvements in casting technology obtained in recent years.

A first series of papers addressing this question was presented by airworthiness officials, both military and civil, of the NATO nations. In a second series, aircraft designers reported on their experience with the introduction of premium castings in aircraft construction. A third series of papers allowed casting technologists to present the current state of the art with respect to casting technology and to challenge the continued application of a casting factor. A final session provided a forum for representatives from the different parties involved to assess the situation as presented by the previous speakers.

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